Reducing environmental impacts of the global rare earth production for use in Nd-Fe-B magnets

How much can recycling contribute?

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vom Fachbereich Bau- und Umweltingenieurwissenschaften – Technische Universität Darmstadt zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften (Dr. rer. nat) genehmigte Dissertation

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Tag der Einreichung: 10.01.2018
Tag der mündlichen Prüfung: 18.4.2018

Darmstadt, Dezember 2018

Hiermit versichere ich, die vorliegende Arbeit selbstständig angefertigt, sämtliche Zitate gekennzeichnet und Literaturquellen sowie verwendete Hilfsmittel vollständig angegeben zu haben.

Acknowledgements

Many thanks to those who have supported me with this work. I would like to thank the whole EREAN team for the good collaboration, the provision of life cycle inventory data, and opportunities for discussions, Matthias Buchert and Liselotte Schebek for the supervision, Liselotte Schebek and Tobias Elwert for correcting the thesis, Françoise Lartigue-Peyrou and Jiawen Ding for their help with Chapter 5, Bo Weidema for his help with Chapter 6, Aida Abbasalizadeh and Winfried Bulach for their help with Chapter 7, Gerd Schmidt for his help with Chapter 8.3.1, and last but not least, Scott Lambert for his encouragement and support.

The work was funded by the European Community's Seventh Framework Programme ([FP7/2007–2013]) under grant agreement no. 607411 (MC-ITN EREAN: European Rare Earth Magnet Recycling Network). This document reflects only the author's views, exempting the Community from any liability. Project website: http://www.erean.eu.

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List of abbreviations

AC: air conditioner

ADP: abiotic depletion potential

A-LCA: attributional life cycle assessment

APOS: allocation at point of substitution

BEV: battery electric vehicle

BRGM: Bureau de Recherches Géologiques et Minières

C-LCA: consequential life cycle assessment

CML: Institute of Environmental Sciences, Leiden University

DC: direct current

EOL: end-of-life

EPS: electric power steering

ERECON: European Rare Earths Competency Network

EV: electric vehicles

GHG: greenhouse gas

HD: hydrogen decrepitation

HDD: hard disk drive

HDDR: hydrogenation, disproportionation, desorption, recombination

(H)EVs: (hybrid and) electric vehicles

HREE: heavy rare earth elements

HTP: human toxicity potential

ILCD: International Reference Life Cycle Data System

LCA: life cycle assessment

LCI: life cycle inventory

LCIA: life cycle impact assessment

LED: light emitting diode

LREE: light rare earth elements

MAETP: marine ecotoxicity potential

MFA: material flow analysis

MRI: magnetic resonance imaging

Nd-Fe-B magnets: neodymium-iron-boron magnets

Nd: neodymium

PCRs: Product Category Rules

PFCs: perfluorocarbons

PM: permanent magnet

RE: rare earth

REE: rare earth elements

REM: rare earth metals

REO: rare earth oxides

REPM: rare earth permanent magnets

RIR: recycling input rate

Sm-Co: samarium cobalt

SSD: solid state disk

SX: solvent extraction

TETP: terrestrial ecotoxicity potential

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

USA: United States of America

VCM: voice coil motor

WEEE: waste electrical and electronic equipment

Zusammenfassung

Die Elemente der Seltenen Erden werden aufgrund ihrer technologischen Bedeutung und geopolitischer Versorgungsrisiken als kritische Metalle eingestuft. Sie werden in einer Vielzahl von Anwendungen eingesetzt, u.a. für Magnete und Leuchtstoffe, Batterieelektroden, Katalysatoren und Schleifmittel. Viele dieser Anwendungen gehören zur den sogenannten "Grünen Technologien"[1] da sie die Energieeffizienz der Anwendungen steigern. Dies gilt auch für Permanentmagnete, die die ökonomisch wichtigste Anwendung der Seltenen Erden darstellen. Neodym, Praseodym, Dysprosium und Terbium werden in Neodym-Eisen-Bor (Nd-Fe-B) Magneten eingesetzt, und die Nachfrage nach Nd-Fe-B-Magneten steigt. Um Versorgungsrisiken entgegenzuwirken, werden seit einigen Jahren Recyclingtechnologien entwickelt, um die Seltenen Erden aus dem Nd-Fe-B Magnetmaterial zurückzugewinnen. Während das Recycling von Produktionsabfällen der Nd-Fe-B- Magnete schon praktiziert wird, beschränkt sich das Recycling von Magneten nach Ablauf der Produktlebensdauer (End- of-life recycling) derzeit weitgehend auf Forschungs- und Pilotprojekte. Über die Sicherung der Versorgung hinaus erwartet man sich vom Recycling von Magnetmaterialien auch eine Entlastung der Umwelt, da die Produktion Seltener Erden oft mit gravierenden Umweltbelastungen (Emissionen von Schadstoffen, Strahlenbelastung, hoher Wasser- und Energieverbrauch etc.) verbunden ist.

Kern der vorliegenden Dissertation ist die Frage, in welchem Ausmaß das Recycling von Seltenen Erden aus Nd-Fe-B Magneten zur Reduktion der Umweltwirkungen der globalen Seltene-Erden-Produktion beitragen kann. Um diese Frage zu beantworten, sind folgende Aspekte relevant:

- die Mengen Seltener Erden, die durch das Recycling von zur Verfügung stehendem Nd-Fe-B-Magnetmaterial zurückgewonnen werden können,
- die Wahl der Technologien / Prozesse, die für das Recycling und die Primärproduktion der Seltenen Erden eingesetzt werden
- Marktmechanismen, die entscheidend dazu beitragen, ob und in welchem Ausmaß die Einführung einer Sekundärroute für einzelne Selten-Erd-Elemente zu einer Reduktion der Produktionsmengen der Primärroute beitragen kann.

Zur Beantwortung dieser Fragen wurden die Ökobilanzierung (Life Cycle Assessment, LCA) und die Materialflussanalyse (MFA) als Methoden eingesetzt. Mittels MFA wurden sowohl die globalen Nd-Fe-B-Materialflüsse, als auch die mit den Materialflüssen verbundenen Elementflüsse der in den Magneten verwendeten Seltenen Erden quantifiziert. Damit konnten die zukünftig erwarteten Produktionsmengen ermittelt werden, aus denen sich wiederum die potentiell für ein zukünftiges Recycling zur Verfügung stehenden Materialien ermitteln lassen.

Für die Abschätzung der zukünftigen Recyclingpotenziale wurden Szenarien aufgestellt. Das mögliche Ausmaß der Sekundärproduktion Seltener Erden aus Nd-Fe-B Material wurde mit den erwarteten Produktionsmengen für Nd-Fe-B-Magnetmaterial verglichen. Die Ergebnisse der Materialflussanalyse zeigen, dass für den betrachteten Zeitraum (2020-30) die Mengen an sekundärem Magnetmaterial (Produktionsabfälle, Ausschuss), die für das Recycling genutzt werden könnten, wahrscheinlich die Mengen an Material aus nicht mehr genutzten Magnetanwendungen (End-of-Life Magnete) (in Tonnen Nd-Fe-B Material) übersteigen werden. Etwa 20 Prozent der globalen Nachfrage nach Praseodym und Neodym, und ca. 22-23 Prozent der Dysprosium- und Terbiumnachfrage könnten durch Sekundärproduktion aus Nd-Fe-B-Ausschuss aus der Magnetproduktion und aus nicht mehr genutzten Anwendun-

[1] Unter den weit gefassten Begriff 'Gruene Technologien' fallen Innovationen mit gesteigerter Energie- oder Ressourceneffizienz bzw. verbesserter Emissionsminderung (siehe e.g. BVB 2009).

gen produziert werden. Die Ergebnisse zeigen auch, dass sich die Bedeutung verschiedener Magnetanwendungen als Quelle für in der Sekundärproduktion nutzbares Magnetmaterial hinsichtlich der anfallenden Mengen über den betrachteten Zeitraum ändert – eine Herausforderung für (potentielle) Recycler, die sich auf einen sich ändernden Mix an Altgeräten einstellen müssen.

Die Ergebnisse der Materialflussanalyse flossen in ein Produktionsmodell ein, welches eine Situation abbildet, in der ein Teil der globalen Nachfrage nach Seltenen Erden durch sekundäre Produktion aus Nd-Fe-B-Magneten (Recycling) bereitgestellt wird. Mittels dieses Marktmodells wurden die Markteffekte auf die Koproduktion Seltener Erden analysiert. Diese Analyse ging ein in eine ‚consequential LCA' (C-LCA), eine Form der Ökobilanz, die sich mit Änderungen von Umweltwirkungen statt deren absoluter Quantifizierung befasst. In der C-LCA wurde die mögliche Einsparung an Umweltwirkungen durch die Umstellung der globalen Produktion von 100% Primärproduktion auf ein Produktionssystem mit sowohl Primär- als auch Sekundärproduktion analysiert. Methodisch lassen sich mit diesem Vorgehen innerhalb einer Ökobilanz Auswirkungen auf einen Markt, in dem Nachfrage und Angebot unausgeglichen sind, untersuchen.

Ergebnisse der consequential LCA Studie zeigen, dass sich durch das Recycling von Seltenen Erden aus Nd-Fe-B Magnetmaterial Umweltwirkungen in der Produktion Seltener Erden gegenüber der Primärproduktion einsparen lassen. Dies liegt an den geringeren prozessspezifischen Umweltwirkungen der Sekundär- gegenüber der Primärroute, aber auch daran, dass bei Einführung einer Sekundärroute eine Reduktion der Primärproduktion ohne eine zu erwartende Verknappung der koproduzierten Seltenen Erden der Primärroute möglich ist, da bei vielen Koprodukten die Produktion die Nachfrage derzeit weit übersteigt. Durch die Einführung des Recyclings kann diese Überproduktion verringert werden. Die einzusparenden Umweltwirkungen der Primärroute übersteigen so in den analysierten Kategorien die zusätzlichen Umweltwirkungen, die durch das Recycling entstehen, um ein Vielfaches.

Zur Durchführung der consequential LCA Studie war eine Ergänzung der Sachbilanzdaten, welche die Grundlage für die Berechnungen liefern, notwendig. Insbesondere standen keine repräsentativen Daten zur Produktion Schwerer Seltener Erden wie Dysprosium aus Ionenadsorptionstonen zur Verfügung. Für diese Produktionsroute wurde ein Datensatz erstellt.

Da die Produktion Seltener Erden aus Ionen-Adsorptionstonen eine der wichtigsten Produktionsrouten, insbesondere für Schwere Seltene Erden wie Dysprosium und Terbium darstellt, kann der im Rahmen der Dissertation erstellte Datensatz als ein wichtiger Baustein in zukünftigen Ökobilanzen dienen.

Des Weiteren wurde eine Ökobilanzstudie zur Abschätzung der Umweltwirkungen eines Recyclingprozesses, der im Rahmen des EREAN-Projektes entwickelt wird, durchgeführt. In diesem Prozess werden Seltene Erden direkt durch Schmelzflusselektrolyse aus für das Recycling zur Verfügung stehendem Magnetmaterial extrahiert. Schwerpunkt dieser Bilanz war nicht wie in der consequential LCA Studie die Beantwortung der Frage nach den insgesamt einzusparenden Umweltwirkungen, sondern eine Abschätzung der prozessspezifischen Umweltwirkungen in Abhängigkeit von Prozessparametern. Die Ergebnisse der Bilanzierung zeigen, dass die Rückgewinnungsrate – also der Anteil der Seltenen Erden im zu recycelnden Magnetmaterial, der als Produkt abgeschieden werden kann – entscheidend für die prozessspezifischen Umweltwirkungen ist. Weiterhin ist die Vorbereitung des Magnetmaterials für die Elektrolyse nicht vernachlässigbar. Vergleicht man die Schätzungen für die Umweltwirkungen des Recyclingprozesses mit denen der Primärproduktionsroute, zeigt sich, dass der Recyclingprozess Potential für sehr viel geringere Umweltwirkungen hat.

Abschließend lässt sich feststellen, dass die (großflächige) Einführung der Sekundärproduktion von Seltenen Erden durch Recyceln von Nd-Fe-B-Magnetmaterial zur Einsparung von Umweltwirkungen der Seltenen-Erden-Produktion beitragen könnte. Momentan sind die potenziell einzusparenden Umweltwirkungen schon allein aufgrund der geringen anfallenden Mengen an recyclebarem Material noch

begrenzt. Diese nehmen jedoch momentan zu. Ob sich das Recycling tatsächlich durchsetzt, hängt u.a. von der Preisentwicklung der Seltenen Erden, dem Einsatz politischer Anreizprogramme, und geopolitischen Faktoren ab. Zumindest in Europa ist es derzeit wahrscheinlich, dass der Einsatz von Förderprogrammen anfangs notwendig wäre, damit die Umsetzung von Recyclingprozessen erfolgt (ERECON. 2015).

Einige Fragen konnten im Rahmen der Dissertation nicht abschließend beantwortet werden. Dazu gehören offene Fragen zur Quantifizierung der Umweltwirkungen, wie die abschließende Beantwortung der Frage, welche Rolle die Emissionen von Perfluorcarbonen, die ein großes Treibhausgaspotenzial aufweisen, in der Primärproduktion von Seltenen Erden tatsächlich spielen. Weiterhin sind genauere Untersuchungen zu ionisierender Strahlung beim Abbau und der Verarbeitung Seltener-Erden-Erze bzw. möglicher Exposition wichtig. Eine Verbesserung der Wirkungsabschätzungsmethoden, die für die Ökobilanzen zur Verfügung stehen, wäre für die Bewertung der Umweltwirkungen Seltener Erden hilfreich. Das betrifft unter anderem die Methoden zur Bewertung der Strahlenbelastung und Ressourcennutzung.

Summary

Rare earth elements (REE) are classified as critical metals because of their technological importance and geo-political supply risks. They are used in a range of applications, including magnets, phosphors, battery electrodes, catalysts and polishing powders. Many of these applications are important in green technologies. Permanent magnets constitute the most important REE application in terms of market size, specifically with neodymium, praseodymium, dysprosium and terbium used in Nd-Fe-B magnets, and the demand for these magnets is increasing. To mitigate supply risks, efforts are underway to develop recycling technologies to retrieve REE from Nd-Fe-B material. Whilst the recycling of industrial Nd-Fe-B scrap is already practiced, recycling of rare earths from end-of-life products is still largely limited to laboratory and pilot projects.

The question to be addressed in this dissertation is: How does the recycling of Nd-Fe-B magnet material reduce the environmental impact of the global REE production for use in Nd-Fe-B magnets? In the global production system, the extent to which environmental impacts can be reduced through the recycling of Nd-Fe-B magnet material depends on the following aspects:

- the possible extent of the recycling activities, i.e. the question of how much REE material can be supplied from secondary magnet material sources
- the choice of technologies applied in primary and secondary REE production
- market mechanisms, which determine whether and to what extent the output of primary rare earth element production is reduced as a consequence of the recycling activities.

To answer these questions, material flow analysis (MFA) and life cycle assessment (LCA) studies were utilized. The MFA study was conducted to quantify material (Nd-Fe-B) and associated substance (i.e. REE) flows for years 2020 to 2030. This was undertaken to identify the potential future size of secondary REE flows from these materials.

Since recycling of REE from Nd-Fe-B magnets is at its early beginnings today, a future outlook was required. The potential role of secondary REE production from Nd-Fe-B material was compared with the expected overall size of future flows in the global Nd-Fe-B production system. The findings from the MFA study were used to model a future production system in which some of the REE demand is met through secondary production from scrap Nd-Fe-B magnets. Market effects on the jointly produced REE in the primary production system were analysed. The environmental effects of changing from the current REE production system based on primary mining to a potential future system in which some of the primary production is replaced by secondary production were analysed in a consequential life cycle assessment study (C-LCA study) – a form of LCA which focuses on changes in environmental impacts, rather than their absolute quantification. The study provides an example of how effects on an unbalanced REE market can be addressed in LCA studies.

The MFA study showed that the amount of industrial Nd-Fe-B scrap available for recycling is likely to exceed achievable potentials of secondary Nd-Fe-B extractable from end-of-life (EOL) devices in years 2020–30 (by mass of Nd-Fe-B). Around 20 percent of global demand of Nd/Pr and of 22–23 percent of Dy/Tb for Nd-Fe-B production can be met from secondary sources from EOL magnets and industrial Nd-Fe-B scrap in years 2020–30. From a recycling perspective, the most promising Nd-Fe-B application groups were shown to change over the time period considered, posing a challenge to recyclers who have to handle the changing mix.

To aid the C-LCA study, a life cycle inventory for in-situ leaching of REE from ion-adsorption deposits was compiled as this was not previously available in the public literature, or in publicly available databases. Results from the C-LCA study show that recycling of REE from Nd-Fe-B magnets would be

beneficial from an environmental perspective due to the lower environmental impacts associated with the secondary recycling process compared to primary production, but also due to the possibility to avoid overproduction for joint productions in the primary production system. The avoided impact from primary production far exceeds the impact from the recycling activity for all analysed impact categories. In addition, the REE production from ion-adsorption clay deposits constitutes one of the most important REE production routes, and the most important production route for heavy rare earths such as dysprosium and terbium. Therefore, the dataset provides an important addition to the REE production datasets currently available.

Furthermore, an additional life cycle assessment study was conducted to assess the potential environmental impacts of a one-step recycling process developed by researchers in the EREAN project. In contrast to the C-LCA study, the focus of this LCA study was on the process-specific impacts associated with the technology as a function of different process parameters.

Results from the analysis of the recycling process developed in EREAN show that the material recovery rate is crucial to the overall impact of the recycling process. Furthermore, the preparation of the magnet material required before the electrolysis also contributes to the overall impact. The comparison of this recycling route with primary production shows that the recycling process has the potential for much lower process-specific impacts than the current REE primary production process.

To conclude, the secondary production of REE from Nd-Fe-B magnets could help reduce the environmental impacts associated with rare earth production. The potential environmental benefits of recycling are currently still limited by the amount of scrap becoming available each year, however, this is expected to increase in the near future. Whether rare earth production from secondary sources actually takes off will depend on the development of rare earth prices, on whether Nd-Fe-B recycling will be politically incentivized, and on geopolitical factors. In Europe, it is likely that political incentives will be necessary to kick-start recycling operations (ERECON. 2015). Further research regarding the magnitude of perfluorocarbons emissions during rare earth electrolysis, which are potent greenhouse gases, and on ionizing radiation associated with rare earth processing, which has been associated with adverse human – and environmental health effects, is recommended. Furthermore, an improvement of the environmental impact assessment methods available for life cycle assessments of REE, especially with regards to ionizing radiation and resource use, would be desirable.

Chapter 1 - Introduction to problem definition and research question

This chapter introduces the role of rare earths in different magnet applications and their role in green technologies. It explains the reasons behind the increasing interest in rare earth recycling from Nd-Fe-B magnets, the implementation of recycling processes for Nd-Fe-B magnets to date and technological challenges associated with their development. The problem definition and research question are introduced, and an overview of the structure of this thesis is given.

1.1. Background to the research issue

1.1.1 Role of rare earths in different magnet applications and their role in green technologies

Rare earth elements (REE) are used in a multitude of applications, including magnets, phosphors, battery electrodes, catalysts and polishing powders. Many of these applications, including magnets, phosphors, batteries and catalysts, are important in green technologies. Often, light REE and heavy REE are distinguished, based on the atomic weights of the elements. Different classifications exist, some of which distinguish between light, medium and heavy rare earths. Here, two groups are distinguished, according to the classification reported in Krishnamurthy and Gupta (2016): light rare earths (LREE) are defined as the elements from lanthanum to gadolinium, and the elements from terbium to lutetium together with yttrium are classed as heavy rare earth elements (HREE).

REE owe their unique physio-chemical properties to their blocked 4f orbitals, a special electron configuration inherent to these elements. The unique properties can be exploited even when the elements are in embedded in crystals or ligands (Lucas et al., 2015). This is convenient for their use in magnetic and optical applications. The use of rare earths in special magnetic alloy material is due to the paramagnetic properties of the rare earth elements, which are due to their unpaired electrons, and the 4f orbital constellation which permits the production of magnetically anisotropic alloys (Krishnamurthy and Gupta, 2016). The microstructure of the magnetic material is also very crucial to the properties of the material (Gutfleisch; Gutfleisch et al., 2011; Yang et al., 2016). $Nd_{12}Fe_{14}B$ magnets contain around 30% of REE by weight, of which, neodymium (Nd) is the main constituent. Nd can be partly replaced by praseodymium which has very similar properties. Dysprosium and terbium are added to increase the demagnetization temperature, thus making the magnet more resistant for use in environments where heat is generated; such as in motors (Gutfleisch et al., 2011).

Permanent magnets constitute the most important application in terms of market value. Nd-Fe-B magnets are the strongest and most common type of rare earth permanent magnet material, offering best performance characteristics for most applications. Samarium cobalt (Sm-Co) alloys are more expensive and used for some specialist applications where resistance to temperature is an issue (Lucas et al., 2015). Nd-Fe-B magnets are used in motors and generators, speakers, for magnetic separation, MRI scanners and other applications. The demand for the Nd-Fe-B magnets has grown in recent years, mainly due to their use in motor (and generator) applications. The strong magnets allow a miniaturization of the motors, which is convenient e.g. when used in consumer electronics and vehicle applications. Furthermore, when compared to alternative technologies, permanent magnets motors are often superior regarding energy efficiency and maintenance costs (Gauß et al., 2016; Buchert et al., 2013; Waide and Brunner, 2011). In recent years, regulations have been put in place requiring the use of efficient motors, which have supported the market breakthrough of Nd-Fe-B magnets used in these applications. Future technological developments which have not yet reached market readiness to date might boost the demand for these materials further– e.g. magnetic cooling (Gauß et al., 2016).

1.1.2 Overview of primary rare earth mining and deposits

Rare earth deposits can be found across all continents, but are only mined by a few countries. China held a near monopoly before 2011, the year of the rare earth crisis (Sprecher, 2016). Since the crisis, primary production has diversified to an extent. Australia currently produces around ten percent of global rare earth supply, followed by Russia, which held a market share of 2% in 2016 by volume (Aspa, 2017). However, Molycorp, one of the main mining companies outside China, had to stop its production since the company could not run at a profit. China is still the main producer at around 80-85% of global production, according to their published 2016 production quota and other officially reported figures (Aspa, 2017; USGS, 2017a). Of the rare earths produced in China, around 55% are mined in Bayan Obo, and 16% from ion adsorption clay deposits (Lee et al. 2017). However, the actual production share from ion adsorption clay deposits is likely to be much larger: Around 30-50% of the actual global rare earth production are expected to be from illegal production (Kingsnorth and Packey, 2018, Packey et al. 2016), and illegal production is likely to be largely from ion adsorption clay deposits (Packey et al. 2016). Furthermore, due to the large extend of illegal production; it is likely that even today, the actual share China holds in global production is higher than reported. Furthermore, the majority of rare earth processing facilities are also located in China.

A detailed global map showing existing mines, deposits and occurrences of rare earth elements compiled by USGS has been published by US Department of Energy (2017). Both mineral and sedimentary deposits are relevant sources of rare earths. Rare earths occur in a large number of mineral deposits, but historically, REE mining has focussed mainly on LREE-rich mineral deposits, i.e. bastnaesite and monazite (Eurare, 2017). Ion-adsorption clay deposits, which occur very localized and are currently mined in Southern China, constitute an important production route for heavy rare earths such as dysprosium (Talens Peiró and Villalba Méndez, 2013). In these deposits, the rare earths do not occur in mineral structures, but are adsorbed to clay particles.

1.1.3 Motivation for recycling

The demand for Nd-Fe-B magnets has grown in recent years, and is expected to do so in the future. The magnets are a crucial “ingredient” in many green technologies such as electric and hybrid vehicles, wind turbines, and many other motor applications. As a consequence, the availability of end-of-life (EOL) magnet scrap is expected to increase in the coming years, and secondary supply is deemed capable of playing a significant role in the supply mix (Yang et al., 2016). Hence, the development of recycling processes is becoming a relevant issue (ERECON[2], 2015).

The main reason why recycling of rare earths has gained increasing attention in recent years is the perceived risk of supply shortages or price fluctuations for these elements, which have been an issue for industry players outside China, the main producer of rare earths on the global market. Recycling is seen a possible strategy to diversify rare earth supply. Other strategies include the development of new mining projects outside China, material development towards a reduced use of the elements which are highest in demand, and material substitution.

Rare earth primary production is associated with environmental impacts during mining and processing (Schüler et al., 2011). The process is elaborate, with high energy and chemical requirements. The elements occur in low concentrations in the ores. They co-occur as a group and jointly with other co-mined metals such as iron, thorium, uranium or titanium.

Rare earths mined from mineral deposits as found in Baotou Obo, China, are open-pit mined. After the extraction and milling of the ore, the rare earth elements are concentrated in a number of physico-

[2] ERECON: European Rare Earths Competency Network

chemical processing stages referred to as beneficiation. During dry ore processing, workers may be exposed to dust containing toxic components present in the ores. In a wet processing step, the rare earth-rich fraction is separated from a concentrated iron ore fraction. Tailings, i.e. the part of the ore which is left behind after the extraction of the rare-earth concentrate and iron ore, mixed with chemicals and waste water from the extraction process, are stored in ponds near the processing site. These tailings contain radioactive thorium and uranium which can be damaging to the health of the workers and local population if inappropriately managed, e.g. in case of infrastructure failure or severe weather events. Besides the ionizing substances which co-occur with the rare earths in the ores, the tailings contain heavy metals, fluorides, sulphides, arsenic and other substances. The largest tailing pond in Baotou Obo lacks sufficient lining, and its contents have been polluting the surrounding ground water reservoirs, with severe health implications for the local population, which has eventually been relocated (Guardian, 2014).

After separation of the rare earth concentrate from the iron ore, the concentrate needs to be further treated to make the REE accessible. For LREE-rich mineral deposits such as bastnaesite-monazite ores mined in Bayan Obo, the acidic processing route is most common (Schüler et al., 2011). The concentrate is roasted in sulfuric acid, leached with water, and the rare earths are precipitated with ammonium carbonate. The rare earth carbonates are then treated with HCl, with brings them into a chloride form, suitable for the following solvent extraction step (Sprecher et al., 2014b).

In the solvent extraction process, the individual REE are separated from each other. Then, the rare earth oxides need to be reduced to metals through an electrolysis process. Especially the last step is associated with high energy consumption (Talens Peiró and Villalba Méndez, 2013). Furthermore, it is likely to be associated with the emission of perfluorocarbons (PFCs), which are potent greenhouse gases (Vogel et al., 2016).

Due to the fact that the rare earths co-occur in the ore, it is not possible to produce them individually. However, the market is not balanced for individual elements, which means that some of the elements are produced in oversupply (Binnemans et al., 2013b). It has therefore been argued that reducing the demand for the primary production of those elements which are highest in demand would reduce the overall impact of primary rare earth production.

At the time of writing, only a small number of life cycle assessment studies had been conducted to quantify the environmental impacts of Nd-Fe-B magnet recycling. However, they agreed with regards to their observations that the impacts for the analysed secondary production routes were found to be lower than those of magnet production from primary REEs. Sprecher et al., (2014b) analysed the environmental impacts of a direct alloy recycling route and found a lower impact than with the conventional magnet production using primary rare earths. The authors also analysed a post-shredder recycling option. That, however, was found to be less attractive due to the very high material losses, but nevertheless preferable over the primary route in terms of environmental impacts. Jin et al. (2016) analysed a different direct alloy recycling route that was shown to have lower impacts than magnet production using primary rare earths. Walachowicz et al. (2014) analysed reuse, direct alloy recycling and indirect recycling (rare earth extraction) as three alternative valorisation options for end-of-life magnets and found all of them to be environmentally advantageous over magnet production from primary REE.

1.2. Problem definition and research question

To date, recycling of rare earths has not been a significant strategy to reduce the supply risks of the Nd-Fe-B supply chain compared to other strategies, such as substitution (Sprecher, 2016). However, with the growing Nd-Fe-B market, this could change in the near future (Yang et al., 2016). Although individual life cycle assessment studies have been conducted, and found the analysed techniques to

be beneficial over primary production, they have focussed on process-specific impacts. The overall change to the impact of the production system is a function of both process-specific impacts and the overall magnitude of the recycling activities, and market effects.

The question to be addressed in this dissertation is to what extent recycling of rare earth elements from Nd-Fe-B magnet material could reduce the environmental impact of the global REE production for use in Nd-Fe-B magnets. The “production system” considered here comprises the global production of rare earths required for the production of Nd-Fe-B magnets.

To what extent environmental impacts can be reduced by the recycling of Nd-Fe-B magnet material depends on the following aspects:

- the possible extent of the recycling activities, i.e. the question of how much REE material can be supplied from secondary magnet material sources
- the respective processing technologies applied in primary REE production and recycling (and, when direct recycling is included, the magnet production processes)
- market mechanisms, i.e. whether and to what extent primary REE production output is reduced as a consequence of the recycling activities.

1.3. Overview of thesis structure

The thesis is structured into eight chapters.

The first chapter presents the background to the research issue. It explains the motivation for rare earth recycling from Nd-Fe-B magnets, and introduces current challenges associated with the development of the recycling processes. At the end of the chapter, the research question is introduced, and an overview of the thesis structure is given.

Chapter 2 gives an overview of the current state of research which has already been undertaken on the subject. It begins with an overview of the recent developments and technological challenges of Nd-Fe-B recycling processes. Then, the main findings from life cycle assessment studies which have previously been conducted to assess the environmental impacts of recycling processes for REEs from Nd-Fe-B magnets are presented. Furthermore, an overview of material flow analyses conducted to quantify recycling potentials of REEs from Nd-Fe-B magnets is provided.

In Chapter 3, an overview of the methods used to answer the research question of this PhD thesis is presented. It begins by introducing the methods used to answer the research question, and then explains how the methods were combined in this thesis to answer the research question.

Chapter 4 presents a scenario MFA (material flow analysis) study, with estimates of Nd-Fe-B material globally available for recycling in the time period 2020-2030, derived through a material flow analysis. From these estimates, the quantities of individual rare earth metals extractable from magnet scrap were calculated, and a production mix presented to denote the possible contribution of secondary rare earths to the overall supply.

In order to answer the overall research question, a life cycle assessment study is applied. Since a representative dataset for the most common primary production route for heavy rare earths, namely the production from ion-adsorption clay deposits, was not available, a dataset was compiled, based on information from the literature and expert opinions. This study is presented in Chapter 5.

In Chapter 6, a consequential life cycle assessment study is conducted to illustrate the impacts rare earth recycling from Nd-Fe-B magnets could have on the overall impact of the global production of rare

earths. This chapter answers the research question for a specific recycling process in which rare earths are extracted from the magnet material. As discussed in Chapter 2, several recycling processes are being developed, with different environmental impacts. Chapter 7 presents a case study for a different recycling process which is being developed at lab-scale. In Chapter 8, the overall research findings are summarized and discussed, and recommendations for further research are given.

For Chapters 4-6, data and information not required for the general understanding of the storyline, such as assumptions made during the life cycle inventory compilation, or background data to the graphs presented on the material flows, are presented as supplementary information in the Annexes (A1-A3).

In this thesis, the abbreviation REE is used as default when speaking of rare earth elements, a term which does not specify whether the elements are in an oxide or metal form. In some cases, it is however necessary to distinguish between rare earth oxides (REO) and rare earth metals (REM). This is particularly important when weights are provided. In that case, it may be specified that the amount of REE is provided in t of REM, for example. The term REM (rather than REE) is also used in Chapter 7 which particularly deals with the process step which produces metals, to emphasize that they are in a metal form.

In some cases, a differentiation between light rare earth elements (LREE) and heavy rare earth elements (HREE) is made in the text, according to the classification reported in Krishnamurthy and Gupta (2016). Light rare earths (LREE) are defined as the elements from lanthanum to gadolinium, and the elements from terbium to lutetium together with yttrium are classed as heavy rare earth elements (HREE). In the context of Nd-Fe-B magnet materials, Nd and Pr are the two main LREE, and Dy and Tb are the two main HREE used (see Chapter 4 and 6). As above for REM and REE, the default term that is used is (L)REE or (H)REE. The use of the terms HREM and LREM has been avoided for the purpose of readability.

Chapter 2 - Current state of research

In this chapter, an overview of the current state of research which has already been undertaken on the subject is provided. It begins by introducing the recent developments and technological challenges of Nd-Fe-B recycling processes. Then, life cycle assessment studies which have previously been conducted to assess the environmental impacts of recycling processes for REEs from Nd-Fe-B magnets are presented. Furthermore, a brief review of material flow analyses conducted to quantify recycling potentials of REEs from Nd-Fe-B magnets is given.

2.1 Development of Nd-Fe-B recycling processes – current state of development and technological challenges

2.1.1 Pre-consumer scrap

A substantial amount of Nd-Fe-B scrap arises at various stages during magnet manufacturing (Anonymous, 2015d; Lyman and Palmer, 1993). Clean and dry scrap, such as waste arising from cutting magnets to shape, can be internally recycled: Short loops make it easier to monitor material composition and contamination. Wet swarf from finishing processes, which amounts to 20-30% of the starting material, can only be fed into indirect recycling processes, due to contamination and surface oxidation (Anonymous, 2015b; Bast et al., 2015; Constantinides, 2015; Tanaka et al., 2013).

2.1.2 First EOL-magnet recycling activities

Recycling of Nd-Fe-B magnet material from applications which have reached the end of their usage period (EOL magnets) still does not play a significant role in Europe (Jones, 2017). Processing in Europe is not currently economically viable, although it has been reported that some processes are not far off their economic viability (Tsamis and Coyne, 2015). Furthermore, some evidence of recyclers purchasing Nd-Fe-B scrap could be found when conducting an internet search (see e.g. Innova Recycling, 2017; Metalltrading, 2017; Walch, 2017). The material is sold on and recycled in China (Elwert, 2017b). In Europe, much of the EOL magnet material contained electronic waste is currently shredded with the steel fraction and lost (Bast et al., 2015; Tsamis and Coyne, 2015). The current shredding and smelting techniques are not suitable for post-shredding recovery of rare earths; and material recovery rates would be very low (Binnemans et al., 2013a; Du, 2014; Sprecher et al., 2014b; Tsamis and Coyne, 2015).

The growing public interest in rare earth recycling from EOL Nd-Fe-B magnets was triggered by the supply restrictions in 2011, and manifested in an increase of research projects devoted to the development of recycling processes. Magnets have been identified as the most important secondary source of rare earth elements in a European context, and the number of patents for REE recycling has also grown rapidly in recent years (ERECON, 2015). In recent years, government-funded pilot projects have been established in Japan to recycle magnets from hard disk drives, air compressor motors and other Nd-Fe-B applications. The magnets were successfully removed from the hard disk drives, and recycled through an indirect recycling route, i.e. the rare earths were extracted from the magnet material (Hitachi, 2014b; Hitachi Ltd., 2013; Mitsubishi Electric, 2014a). However, it is unclear if these processes are already viable without public funding, and whether they remained operational beyond the period of public funding support. There is some indication that the costs of recycling may currently be prohibitive, at least for the recycling of hard disk drives (Sprecher, 2016), which contain none, or only very small amounts of the valuable heavier rare earths (Binnemans et al., 2013a). The information which has led to this conclusion has been obtained from recyclers in Japan and the Netherlands, both countries with high labour costs. However, some recyclers and manufacturers are extracting and stor-

ing EOL-magnets from compounds in anticipation of a market to be established in the near future (Anonymous, 2015f; Buchert et al., 2013; Dupont and Binnemans, 2015; Yang et al., 2016). A start-up company for the recycling of REEs from EOL magnets with a new patented hydrometallurgical process has been founded in the US (REEcycle, 2015). In China, component reuse from waste electronic equipment is common (Yang, 2008; Yang and Wu, 2016). EOL-magnets from hard disk drives (HDDs) are often extracted by informal recyclers and reused in other applications, e.g. fridge magnets or children's' toys (Anonymous, 2016b). It should be noted that the recycling processes being developed in recent years have focused on the recycling of sintered Nd-Fe-B magnets as opposed to bonded Nd-Fe-B magnets, which have also gained popularity in recent years, but are produced in much smaller quantities compared to the sintered Nd-Fe-B magnets. Bonded Nd-Fe-B magnets often replace small ferrite magnets in small automotive motor applications, since they make more efficient motors and are lighter in weight (Grieb, 2014; Gutfleisch et al., 2011).

Besides the development of technologies to extract EOL magnets from appliances and recycle them, options to modify the current recycling processes in a way that REEs could be efficiently recovered after the magnets have passed through the shredders are also being investigated by researchers (Yang et al., 2016).

2.1.3 Technical challenges

Researchers in the EREAN project are working on the direct and indirect recycling of Nd-Fe-B magnets (EREAN, 2015). The direct recycling involves the reprocessing of the material into new magnets. Indirect recycling routes involve the chemical decomposition of the magnets and extraction of (individual) REEs. Before the magnets can be used as an input material for an indirect recycling process, or a reuse of the magnets, magnets need to be extracted from their devices and demagnetized, as outlined below. These steps are also necessary for some direct (magnet material) recycling routes. Other direct recycling routes use hydrogen treatments to extract and demagnetize the magnet material.

Extraction

To feed magnets from EOL-components into a recycling system, the recyclers need to efficiently collect and detect the presence of the magnet material in the appliances. This first step, i.e. the separation of the magnets from EOL-appliances, has been identified as one of the key barriers to Nd-Fe-B magnet recycling (Binnemans et al., 2013a). The magnets come in different shapes and sizes from a large variety of applications (Chapter 4) which poses a challenge to the automation of the extraction step. However, Hitachi has already developed an automated process for the extraction of the magnets from hard disc drive and air conditioner motors. Furthermore, prototypes for automated removal of magnets from electric vehicle traction motors have been developed successfully in a recent pilot study (Bast et al., 2015).

Demagnetization

Demagnetization of the magnets is required to facilitate the further processing or reuse of the magnets. It can be achieved by heating the magnets above the Curie temperature, or by exposing them to an external magnetic field. Glues and other organics need to be removed prior to demagnetization via heating to avoid the formation of hydrocarbon containing vapours (Binnemans et al., 2013a).

An alternative to mechanical extraction and demagnetization is hydrogen decrepitation, which achieves both in one step. The magnets are transferred into a hydrogen atmosphere to achieve the absorption of hydrogen by the magnet material. In this process, the magnet decrepitates into a demagnetised, hydrogenated powder (Walton et al., 2015). Hydrogen decrepitation generally requires a

removal of the coatings or glues prior to the process to expose the magnet material surface to the hydrogen.

Reuse

In many cases, the components (e.g. motors) reach the end of their lives before the magnets do. If the magnet is not deteriorated, the reuse of magnets would be preferable to any form of recycling in terms of environmental impact, since less processing would be required. The reuse route involves demagnetization and cleaning of the magnets (Bast et al., 2015; Walachowicz et al., 2014).

The main issue with reuse is associated with changing design requirements, e.g. the shapes of the components are likely to change over the typical life time of most magnet applications (MORE, 2014). Although it is possible to cut a used, big magnet to size for smaller applications, the magnet composition and microstructure would have to be suitable to meet the specification of the new application.

Direct recycling (direct alloy processing)

The material treatment undertaken in direct recycling is conducted to enable the production of the magnet in a different shape and/ or with different material properties. The latter can be modified via control of the microstructure through application of heat and/or pressure, which has a large impact on the specification of the magnet, or by the additions of small amounts of rare earths. The direct recycling processes are more flexible than the reuse options in that the material compositions can be modified (the modification of the shape is possible with the reuse option to some extent when larger magnets from EOL magnets are cut to shape).

One direct recycling option is hydrogen decrepitation followed by re-sintering of the magnet material, developed by researchers at the University of Birmingham. This route requires some rare earth hydrides to be added to the decrepitated magnet powder; the powder to be re-milled, aligned (magnetized), pressed to shape and resintered into new magnets. An alternative processing route is named “Hydrogenation, Disproportionation, Desorption, Recombination” (HDDR). This route is suitable for the production of an anisotropic coercive powder which can then be used to make cold-pressed, injection-moulded magnets. Another direct recycling route is via melt-spinning. The ribbons produced via this route can be used to produce bonded magnets. Alternatively, they can be used as a starting alloy for the production of sintered magnets (Yang et al., 2016).

However, direct processing of alloys is normally associated with quality losses – (MORE, 2014; Walton et al., 2015; Yang et al., 2016). Even though the processes are conducted in an inert atmosphere, (e.g. under argon atmosphere), it is technically challenging to prevent a loss of magnetic properties, since it is very difficult to fully prevent contamination of the material, one of the reasons being that rare earths are highly reactive when exposed to the elevated temperatures used during heat treatments. For the hydrogen decrepitation process, the oxidized fraction of the magnet material does not decrepitate in hydrogen (Binnemans et al., 2013a). For the recycling via re-melting and re-sintering route, if the recycled material is partly oxidized, it can be “diluted” with a primary alloy to minimize the loss in magnetic properties (Bast et al., 2015; Walachowicz et al., 2014).

The main difficulty with the direct recycling processes described above is associated with the fact that the magnets are sold on the market with a specification, i.e. as for magnets produced from primary REEs, it is important that the quality of the secondary magnet produced is controllable and the variation of the properties can be minimized (Yang et al., 2016). One of the challenges here is the great variety of Nd-Fe-B applications – to obtain a product with a small variation in properties, it would be necessary to monitor the composition and potential contamination of the input material stream: Even variations in material composition of different HDD magnets are mentioned in the literature a potential

issue for this route (Yang et al., 2016 citing Ueberschaar and Rotter, 2015). In principle, direct recycling routes are favourable over indirect recycling in terms of their impact on the environment, since typically, a smaller number of processing steps, i.e. less modification of the material, is involved. For the hydrogen decrepitation and re-sintering route and for a re-melting route (re-melting of scrap magnets before re-sintering), this has been confirmed through LCA studies (Sprecher et al., 2014b; Walachowicz et al., 2014). Direct alloy recycling is also likely to be advantageous over indirect recycling in terms of processing costs. The challenge is to identify a route which produces marketable magnets and is economically viable.

Indirect recycling

Indirect recycling processes produce individual rare earth oxides which can be of qualities comparable to primary rare earths. They are generally more elaborate than direct material recycling processes, with more processing steps involved; but offer greater flexibility since they produce the individual rare earths which can then be used again for the manufacturing of new magnets, or even for other applications. It can be assumed that rare earths of the same purity as primary rare earths would sell equally well as primary rare earths. Indirect recycling not only provides more flexibility regarding the output, but also regarding the variability of the input material. Indirect recycling processes are generally better suited for the processing of magnet materials of different compositions and with different levels of contamination /oxidation (Binnemans et al., 2013a). However, some of the simpler pyrometallurgical processing routes (direct remelting) are not suited for the processing of oxidized magnets (Binnemans et al., 2013a). Environmental impacts are likely to be lower than for rare earths produced through primary production routes, which has been shown for the one indirect recycling route which had been analysed at the time of writing (Walachowicz et al., 2014). Hence, the challenge is to develop recycling processes which can compete with primary rare earths in terms of their production costs.

Hydrometallurgical extraction of rare earths from Nd-Fe-B magnets requires leaching, separation of individual rare earths, precipitation and conversion to oxides or fluorides (Yang et al., 2016). In primary rare earth production, the separation of rare earths is commonly done with solvent extraction (Leveque, 2014). Hydrometallurgical methods require the use of potentially large amounts of chemicals for the reactions and generate waste water (Binnemans et al., 2013a; Chun-Sheng et al., 2016). The separation of rare earth mixtures is difficult due to their chemical similarity, due to similar electronic configurations (Gupta and Krishnamurthy, 2005). The separation processes make use of the small differences in basicity resulting from differences in the ionic radii of the individual elements (Gupta and Krishnamurthy, 2005). In primary production, the large variety of individual rare earths present in the ores generally necessitates a number of extraction stages with different extractants (Chun-Sheng et al., 2016). Whilst both primary rare earth production and rare earth extraction from magnets require a separation step, one advantage of magnet recycling over primary production lies in the smaller number of rare earth elements present in the starting material; as a result, the separation process can be shortened. It may be unnecessary to separate praseodymium from neodymium if the rare earths are destined for the use in the production of new magnets (Walachowicz et al., 2014; Yang et al., 2016).

As an alternative to hydrometallurgical separation processes, pyrometallurgical extraction processes can be used. They generally require a smaller number of processing stages than hydrometallurgical processes, but more energy is required for processing (Binnemans et al., 2013a). Combinations of pyro-and hydrometallurgical recycling processing have also been trialled successfully – see e.g. Önal et al., 2015, where a sulfation roasting process is applied prior to leaching to facilitate the separation between rare earths and the iron fraction.

2.1.4 Other challenges

Besides the technical difficulties, the development of a recycling system for rare earth elements from Nd-Fe-B magnets is challenged by some other developments: The main motivation to promote recycling was the need to obtain a better supply chain resilience after the 2011 supply restrictions. In order to become less vulnerable to rare earth supply risk and/or price volatility, different strategies have been followed by the industry players in recent years. These include supply diversification by starting new mines, and demand-side diversification, such as the development of new production processes which allowed a reduction in use of the most critical/expensive heavy rare earths in magnets, the use of alternative magnet materials, or induction motors (see Binnemans et al. 2013, Sprecher, 2016, Yang et al. 2016, Schüler et al. 2011).

Since a continuous, homogenous material input stream is desirable for some recycling processes (especially direct alloy reprocessing); the diversification in material composition poses a challenge to potential investments into recycling (Bast et al., 2015, Walachowicz et al., 2014). A perceived lower risk also lowered the rare earth prices in recent years, which reduces the incentive to invest into recycling schemes. The reduction in heavy rare earth contents also reduces the value of the EOL magnet material, with the same effect.

2.2 MFA studies conducted to quantify recycling potentials for REEs from Nd-Fe-B magnets (and other key sources)

In recent years, a number of material- and substance flow analysis (MFA/SFA) studies have been conducted on – or including – REE in Nd-Fe-B magnets (Alonso et al., 2012; Du and Graedel, 2011, 2013; Elshkaki and Graedel, 2013; Gauß et al., 2016; Guyonnet et al., 2015; Kim et al., 2015; Rademaker et al., 2013; Sprecher et al., 2014a; Swain et al., 2015; van Eygen et al., 2016; Zepf, 2013, 2015, 2016). The large number of studies illustrates the increasing interest in rare earth metal recovery from scrap magnets in recent years. Many of these studies have tried to answer the question of whether recycling of REE from EOL magnets can alleviate REE supply shortages. A related topic assessed in these studies is about the material requirements for emerging (green) technologies – a topic for which the availability of secondary REE sources also plays a role. The studies were conducted against the background of REE supply uncertainties faced by companies outside China, the main producing country, with implications for green applications relying on Nd-Fe-B magnets in mind. It is clear from these studies that the demand for REE for use in Nd-Fe-B magnets is increasing at a fast pace, which indicates that the establishment of industrial recycling processes is becoming a more relevant issue.

A common finding in many studies was that recycling will not be able to meet a large fraction of REE supply in the near future, but that this fraction is increasing, with the delay due to the time lag associated with product lifetimes and the predicted growth of Nd-Fe-B applications – (see for example (Alonso et al., 2012; Bradshaw et al., 2013; Buchert et al., 2011; Rademaker et al., 2013; Seo and Morimoto, 2014). A report published by the European Rare Earths Competency Network (ERECON) comes to a similar conclusion. The authors highlight the dramatic increase in products which contain Nd-Fe-B magnets, and their importance in green energy technologies, and identify a list of priority products to target to further recycling of REEs from magnets in Europe (ERECON, 2015).

Despite the large number of related studies, they were typically based on specific regions, countries, and/or specific application groups of Nd-Fe-B magnets, but did not have a global focus and a comprehensive view on sources for Nd-Fe-B scrap as deemed required to answer the research question for this thesis. However, the studies provided a useful basis and source of detailed information on Nd-Fe-B magnet compositions in different applications, market shares of respective applications with Nd-Fe-B

magnets, expected future material development and development of markets for individual appliances for the study presented in Chapter 4. Furthermore, the work by and personal communication with S. Constantinides was helpful in providing an estimate of the importance of Nd-Fe-B magnets in different applications in recent years (Constantinides, 2012, 2014a, 2014b, 2014b, 2014c, 2015).

2.3 Summary of findings from previous LCA studies conducted to assess environmental impacts of Nd-Fe-B recycling processes

Rare earth recycling processes from Nd-Fe-B magnets have recently gained interest, and so has the interest in the environmental impacts associated with these processes. At the time of writing, only a few (attributional) life cycle assessment studies of earth recycling processes from Nd-Fe-B magnets had been published (Akahori et al., 2014; Jin et al., 2016; Sprecher et al., 2014b; Walachowicz et al., 2014). Whilst not many studies had been published on this topic, those which compared recycling of Nd-Fe-B material against REE primary production, or Nd-Fe-B production using primary REEs, all found the recycling processes to be advantageous from an environmental impact point of view[3] (Bast et al., 2015; Jin et al., 2016; Sprecher et al., 2014b; Walachowicz et al., 2014). Furthermore, there are some ongoing and recently completed projects which investigate(d) the environmental impacts of different REE recycling processes from Nd-Fe-B magnets, including (but not limited to) the Demeter and Rare[3] projects coordinated by KU Leuven, the Swiss E-RECMET project on recovering critical metals from electronic waste, and a project conducted at BRGM funded by the French National Research Agency (Beylot, 2016). Hence, results of further LCA studies analysing different recycling processes can be expected in the near future.

The process which requires least processing is magnet reuse. The magnets are extracted and cleaned as described below. Magnets are often fit for reuse when the components which contain the magnets, or the appliances containing their components, reach the end of their lives (MORE, 2014). Unsurprisingly, this is the most environmentally advantageous processing route, which has been demonstrated in the LCA study by Walachowicz et al., (2014), but markets are seen as limited by the changing design of the magnets, both in terms of shape and composition (MORE, 2014; Walachowicz et al., 2014).

The extraction of the magnets from EOL components is necessary before the magnets can enter any further treatments. Depending on how the magnets are installed in the compound, and due to the large variety of Nd-Fe-B magnet applications and component designs, this step can be difficult, and it is important to choose the right technologies for this processing step. A recycling process starting with the shredding of hard disk drives containing Nd-Fe-B magnets, and followed by leaching of the Nd from the magnet material, has been assessed in an LCA study (Sprecher et al., 2014b). The important issue with this process was the very low recovery rate of magnet material during shredding. The trial study for this recycling process, which started with shredding of hard disk drives containing Nd-Fe-B magnets, found that only ~10% of the magnet material fed into the shredder was recovered (Sprecher et al., 2014b). Furthermore, the shredding process introduces oxygen and other contaminants into the magnet material. The study found the process to be less environmentally favourable than another recycling route in which the magnet material was first extracted from the component through a hydrogen treatment, a process which incurs only small material losses – see also Walton et al., (2015). Besides the hydrogen treatment; magnets can be mechanically extracted from their compounds, either by manual disassembly, or machine-assisted extraction. Manual disassembly may be cost-prohibitive, at least for applications which contain small magnets processed in higher income countries. Therefore,

[3] Analysed systems comprised either the extraction of REEs from scrap magnet material, the reprocessing of Nd-Fe-B magnet material into a new material, or the preparation of Nd-Fe-B magnets for reuse in new magnet applications.

the development of extraction techniques and the consideration of EOL at design stage for new applications are crucial. Walachowicz et al., (2014) found that the environmental impacts from automated extraction, cleaning and demagnetizing were mainly due to the cleaning (polishing) material used to remove surficial impurities, and the energy consumption during infrared demagnetization (MORE, 2014; Walachowicz et al., 2014).

After extraction, the magnets material can be reprocessed via different (pyrometallurgical) direct material recycling processes, which process the magnet material. In these processes, the material structure and shape of the final magnet can be modified (and thus, its properties), but the composition is largely maintained (sometimes, small modifications are made, such as the addition of small quantities of REEs). Options include strip-casting, melt-spinning, remelting, hydrogenation decrepitation (HD) followed by resintering, and HDDR (Hydrogenation, Disproportionation, Desorption and Recombination) (Walton et al., 2015). These are generally expected to be more environmentally advantageous than processes which extract the rare earths from the magnet material, since less processing and modification of the material is required (Gauß et al., 2015). The LCA studies which have been conducted to date have confirmed this – results have shown clear environmental benefits over primary production processes for the analysed routes, namely hydrogen decrepitation of scrap magnets and resintering into new magnets, and remelting of magnet material (Jin et al., 2016; Sprecher et al., 2014b; Walachowicz et al., 2014)[4]. It should be noted that the analysed remelting process required the secondary material to be mixed with primary material to achieve a sufficient quality of the product, and despite this, it has been questioned whether there would be a market for this type of product (MORE, 2014). According to Jin et al. (2016), their analysed recycling process, which follows a similar processing route as the process analysed by Sprecher et al. (2014b), even produces a magnet of superior quality when compared with the starting material. In summary, results of all three LCAs studies conducted to assess the environmental impacts of the direct magnet recycling routes showed environmental benefits over routes producing magnets with rare earths with primary REEs.

Another option is to extract the rare earths from the magnet material (indirect recycling of REEs from magnets). This is more complex as it involves more processing steps, but offers more flexibility regarding the input material compositions and contamination level. For this reason, it is seen as the most promising type of route in terms of finding a market for its products (MORE, 2014). One LCA study was conducted on a full hydrometallurgical extraction route, which involves extraction of the magnet from its compounds, followed by leaching of the magnet material, removal of impurities (iron, cobalt) via precipitation, and separation of rare earth into the light and heavy fractions (Nd/Pr and Dy/Tb) (Bast et al., 2015; Walachowicz et al., 2014). The environmental impacts of this process were compared against those of the production of rare earths through a typical primary production route. Results showed environmental benefits of the secondary production route over the primary rare earth production route. One advantage of the recycling process over the primary production of REEs lies in the fact that the complex separation of REEs can be shortened, since the magnet scrap contains a smaller variety of individual rare earth elements than the ore which is typically processed – see e.g. Schüler et al., (2011) for typical ore compositions.

Whilst the studies conducted to date have provided an important insight into the process-specific environmental impacts of some of the recycling processes developed to date, they have not focused on the potential change in environmental impact rare earth recycling from scrap Nd-Fe-B magnets could have. This question is addressed in Chapter 6 through a consequential LCA study which considers the potential effects a recycling system on the global primary REE production system.

[4] An own life cycle inventory analysis conducted for a similar process developed in the EREAN project showed very similar results to those presented in Sprecher et al. (2014b).

Chapter 3 - Methods used in this thesis

3.1. Introduction to methods used in this thesis

This chapter presents an overview of the methods used to answer the research question. It begins by giving a brief introduction of the methods used to answer the research question, and then explains how the methods were combined in this thesis to answer the research question.

3.1.1 Material flow analysis

Material flow analysis (MFA) is used to analyse flows to and from material-based systems, as well as stocks inside the system (Brunner and Rechberger, 2016). Both the flows from nature to the anthroposphere and the release of flows from the anthroposphere back to nature can constitute issues: resource depletion and environmental degradation are issues associated with resource extraction, and emissions to nature can cause environmental pollution (Bao et al., 2010). The quantification of flows of either substances or materials is used to obtain an understanding of the system, which forms the basis for the management of resource extraction, emissions and waste flows[5]. MFA studies can help identify hotspots regarding material flows and stocks which need to be managed, such as the early recognition of depletion or accumulation of materials and substances. The information can be helpful to inform decision makers in the fields of resource policies, design and material science, and players in the material supply chain, including mining, processing, recycling and waste management. Due to the increasing diversity of materials used in manufacturing, the method is becoming increasingly important for analysis and planning. One possible application of the MFA method is the comparison of substance flows from the geosphere into the anthroposphere, compared against the quantities which circulate in the natural environment, which can provide an indication of the relevance of potential impacts of man-made flows on natural cycles. Such an analysis has been conducted for cadmium, which is accumulating in soils (Brunner and Rechberger, 2016). Other applications include the analysis of material flows between regions or countries, i.e. within the anthroposphere, to identify the pathways of certain materials and substances within the economy.

3.1.2 Life cycle assessment

Life cycle assessment (LCA) is a technique used to assess environmental impacts of products, processes and services. It has been developed since the 1990s. Nowadays, the approach is well-accepted, and commonly used, although the development is ongoing, e.g. in the area of impact assessment. International standards exist to guide the practitioner (DIN EN ISO, 2006a, 2006b). Since the standards cover a wide range of possible applications of the technique, they must leave room for interpretation; hence, their detailed interpretation is being debated in the LCA community. For LCA studies aimed at products, the implementation of the standard has been further detailed in so-called Product Category Rules (PCRs), which specify further requirements for environmental product declarations (EPDs), i.e. LCA studies conducted for specific product groups.

The systematic analysis is commonly used to guide decision-making with regards to the environmental aspects of alternative choices. This is done by communicating the environmental performance of alternatives. Example applications include green marketing to guide consumer purchasing decisions, strategic planning at organizational, company or policy level, and priority setting regarding process design or –redesign (DIN EN ISO, 2006b). Another, less common application of LCA studies is the monitoring of environmental impacts (Ekvall et al., 2016).

[5] In Brunner and Rechberger (2016), substances are defined as chemical elements or compounds composed of uniform units, i.e., materials homogenous at structural level.

The standard specifies clear rules regarding the general procedure of LCA study. The general idea of the method is summarized as follows: “LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope“. The general procedure is sub-divided into four phases: The goal and scope definition phase, the inventory analysis phase, the impact assessment and the interpretation phase. Results of the LCA study are always expressed in relation to a reference for which both input- and output flows (life cycle inventory data) and the quantitative results of the analysis are reported: the so-called functional unit. A clear definition of the goal and scope of the study is important, and has implications for the scope, system boundary and level of detail required for the study. Another purpose of the goal and scope definition is to clearly communicate which questions the LCA study intends to answer, and which it does not want to answer; i.e. where other techniques for environmental management are required. In the second step - the inventory analysis phase - inputs to and from the analysed system are compiled. In principle, this step can be compared with a material flow analysis. In the next step (impact assessment phase), the life cycle inventory flows are evaluated with regards to their environmental damage potential. The significance of different environmental impacts is quantified to provide information on the relevance of different environmental impacts associated with the studied system, and the hotspots within the system which mainly contribute to the respective category. The last phase of the LCA study is the interpretation phase. This step is conducted to ensure the results of both the life cycle inventory and impact assessment phases sufficiently address the defined goal and scope of the study. Limitations and uncertainties regarding the results, which might stem from data gaps or limitations associated with the impact assessment methods, should be highlighted. For example, if environmental impacts important to the system are known of, but not covered by existing life cycle impact assessment methods, this should be addressed (at least highlighted) in the interpretation phase.

Life cycle assessment studies can be of consequential or attributional nature. Although the exact distinction between attributional (A-) and consequential (C-) LCA is still being elaborated by the scientific community, the following aspects highlighted in the literature are relevant for a distinction:

First, A- and C-LCA differ in terms of their goal and scope definitions: Attributional LCA studies ask about the environmental impact associated with (attributed with) products, processes, or services, whereas consequential studies ask about the environmental impacts associated with the change (in impact) caused by a decision (Ekvall, 2002; Ekvall et al., 2016; Sonnemann and Vigon, 2011; Zamagni et al., 2012). Since attributional and consequential studies answer different questions; the results commonly differ depending on the chosen approach (see e.g. Brander et al., 2008; Kua and Kamath, 2014; Plevin et al., 2014).

Secondly, A- and C-LCA differ in how the modelling is conducted. In attributional LCA studies, the flows (and hence their associated impacts) are allocated according to a normative rule, e.g. the mass, value, energy content of the co-products (Ekvall et al., 2016, Finnveden et al., 2009). In consequential LCA studies, the output which determines the production quantities is identified, and impacts of changes in demand for the determining product on the co-products are handled by system expansion. This has implications for both the scope of the study, and the life cycle inventory compilation for the foreground system. In C-LCA studies, the compilation requires the identification of affected systems. “Activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit” (Ekvall et al., 2016 citing Sonnemann and Vigon, 2011). This means that flows outside the product system are considered (Brander et al., 2008). For example, assessing the environmental impacts of a policy to extend the use (and crop production) for biofuels, the additional space required to grow the crops needs to be obtained by assigning land for this purpose, which means that the previous land use type may need to happen elsewhere. To take these effects into account, they are included in the system boundary.

Ideally, different datasets should be used to model the background processes in attributional or consequential LCA studies, following the principles described above. The ecoinvent database (V.3.2) provides background datasets suitable for attributional or consequential LCA studies. There are three different system models, which differ in how market and transforming activities are linked – two for attributional and one for consequential modelling. All three are composed of transforming activities (production or transformation processes) and market activities. Markets contain information on which processes supply to which market, i.e. how important which transforming activity is in the background system. They supply the inputs needed by the transforming activities. The system model provided for consequential LCA studies is called “Substitution, consequential, long-term“. Multi-output processes are not sub-divided by allocation, i.e. partitioning, as in attributional system models. Instead, by-products are linked to other processes which are being replaced /substituted. This is also known as system expansion. Furthermore, when linking the processes, constraints in the system are taken into account: Only unconstrained markets can react to changes in demand, and are linked with the transforming activities.

3.2 How were the methods combined to answer the research question for this thesis?

The methods used to answer the research question are material flow analysis and life cycle assessment. The data required for the LCA and MFA analyses were compiled from the literature, complemented with discussions with researchers and industry experts in the respective fields. An illustration of which methods were used for which research chapter, and how the results from individual chapters were combined, is given in Figure 1.

The first step necessary to answer the research question for this thesis - to what extent recycling of rare earth elements from Nd-Fe-B magnet material could reduce the environmental impact of the global REE production for use in Nd-Fe-B magnets - was to understand the possible extent of the recycling activities, which (assuming the recycling is politically incentivized), again is determined by how much REE material can be supplied from secondary sources, i.e. magnet material from EOL magnets and industrial magnet scrap. The MFA method was used to quantify material (Nd-Fe-B) and associated substance (REE) flows to identify the potential future size of secondary REE flows from these materials in a structured and systematic fashion. Since recycling of REE from Nd-Fe-B magnets is at its early beginnings today, a future outlook of the MFA study and scenario assumptions was required. The potential role of secondary REE production from Nd-Fe-B material was quantitatively compared with the expected future size of the flows in the global Nd-Fe-B production system. A distinction of different groups of Nd-Fe-B applications, i.e., the part of the analysis conducted at material level, formed the basis of the analysis. This was crucial since the expected demand growth, market share of applications using Nd-Fe-B magnets, magnet weights, typical product lifetimes and the potential to recycle EOL magnets differ between the application groups. The substance level was taken into account since different primary production routes, different market situations and “degrees” of criticality are relevant for individual REE, and compositions of Nd-Fe-B magnets differ between application groups. This level of detail was required for the C-LCA study (Chapter 6). A detailed description of the MFA study and its results are provided in Chapter 4.

In the C-LCA study, the demand for REE used in Nd-Fe-B magnet determined through the MFA was used to quantify the size of the functional unit. The demand for REE used in magnets was based on the MFA results from Chapter 4. The analysis presented in Chapter 6 shows that the REE used in Nd-Fe-B magnets together determine the overall production volumes for all analyzed deposits. However, since the global REE production system is considered in the C-LCA study, the demand for the joint REE also needed to be fulfilled by the same production system, and had to be quantified. The functional unit therefore comprises the annual global production of REE to meet the demand for individual

lanthanide elements from lanthanum to lutetium plus yttrium, excluding promethium, at >99% purity of the oxides. The secondary rare earth production volumes obtainable from Nd-Fe-B magnet material, also estimated through the same MFA study, were used as a basis to construct the production model for the consequential LCA study, constructed to answer the question of how to model the avoided primary production of “magnet REE” and their co-products. More detailed explanations on the use of the MFA results in the C-LCA study can be found in Chapter 6.

To be able to conduct the C-LCA study, a data gap needed to be filled in order to be able to model the most common production route for heavy rare earths such as dysprosium (in-situ leaching from ion-adsorption clay deposits). A life cycle inventory dataset was compiled for this route, based on information from the literature and discussions with industry experts (Chapter 5).

The overall result, obtained through a combination of MFA and LCA studies, is a quantitative estimate of global environmental impacts which can be avoided through the introduction of a secondary rare earth production system through recycling of Nd-Fe-B material.

In Chapter 7, a life cycle assessment study for an alternative REE recycling process is presented. Whilst this is not linked with the C-LCA study, it gave some additional insights on uncertainties associated with the assessment of the technology being developed at lab-scale, and how they can be addressed in practice[6]. Furthermore, a review of the relevant literature highlighted that PFC emissions (with very potent greenhouse gas potentials) may have not been adequately represented in existing life cycle inventories/ studies on primary rare earth production – an issue which requires further investigation.

[6] In this study, they were handled by sensitivity analyses. Quantitaitive results on material recovery rates for the process where not available at the time the study was conducted, so a a possible range was assumed to test the influence of this factor.

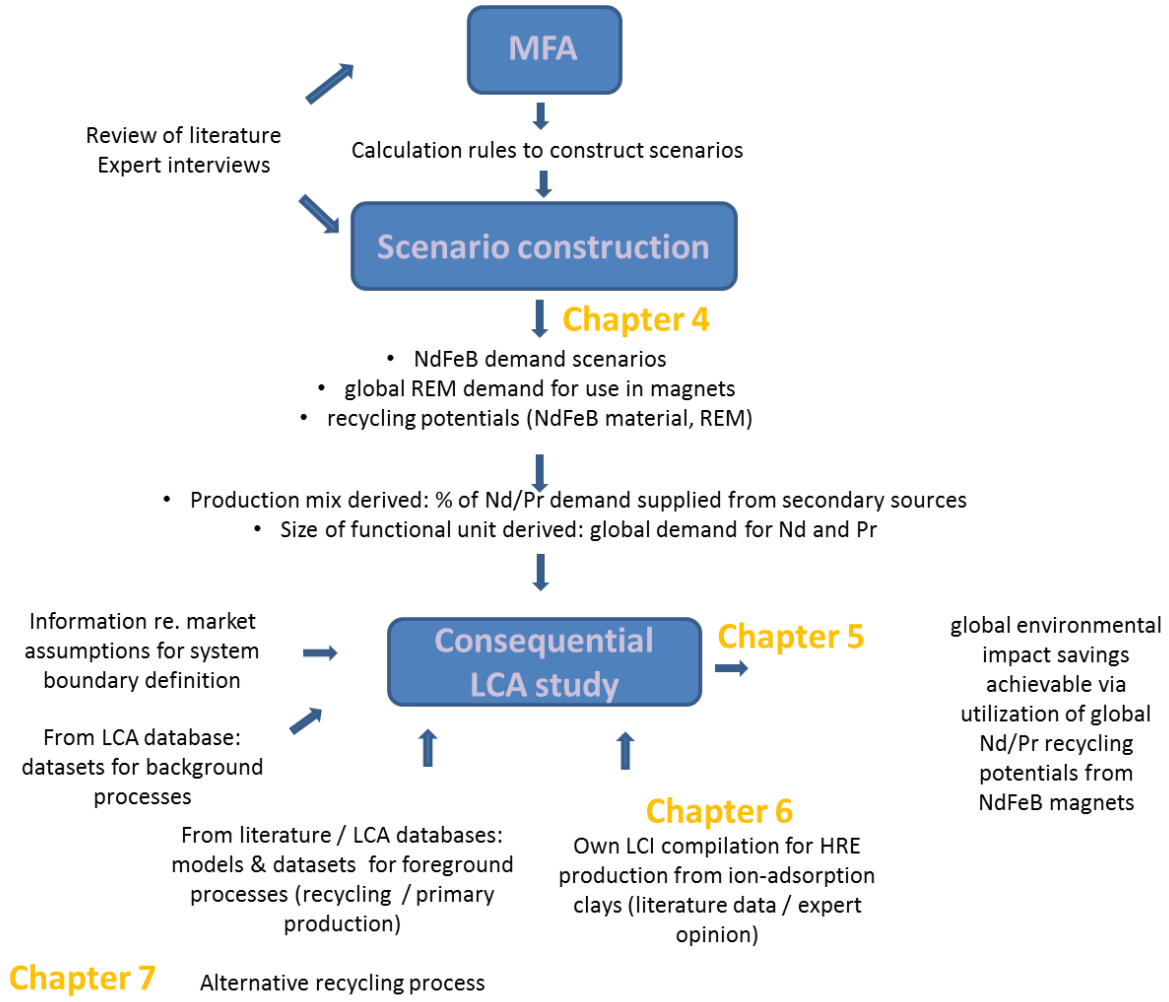

Figure 1: Overview of chapters and methods used

Chapter 4 - How much recycling is possible?

In this chapter, a detailed study of rare earth recycling from sintered Nd-Fe-B magnets is presented. The analysis provides an important starting point for the assessment of the overall role recycling could play in reducing the overall environmental impact of global rare earth supply, since the availability of scrap is one crucial factor in the establishment of an economically viable secondary supply chain. The chapter focusses on the physical availability and practical accessibility of end-of-life and manufacturing scrap. End-of-life magnets from eleven different application groups and industrial scrap were quantified through a dynamic material flow analysis. Demand scenarios for REE used in Nd-Fe-B magnets were constructed. Based on these figures and typical product lifetimes, estimates of quantities for secondary REE which can be produced from scrap Nd-Fe-B material are provided. The modelled scenarios show that between 18 and 22 percent of global light REE (Nd and Pr) and 20–23 percent of heavy (Dy and Tb) REE demand for use in Nd-Fe-B magnet production can be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30 (ranges of values for individual years and scenarios).

4.1 Introduction and goal of this Chapter

Current recycling rates for REEs from EOL-magnets are very low, since recycling schemes are not yet in place. Due to the large number of applications containing Nd-Fe-B magnets, it is not obvious from the outset which applications to target for recycling. The different applications vary in terms of ease of collection and disassembly, and in terms of Nd-Fe-B material value. Previously conducted MFA studies on the potential for secondary REE production from Nd-Fe-B magnet scrap have focused on different regions or Nd-Fe-B application groups.

Whilst numerous authors have made efforts to quantify the potential supply of secondary REE from post-consumer (EOL) Nd-Fe-B magnets (see section 3.1.1), the studies undertaken were less comprehensive in scope than required for this thesis. Also, whilst the focus has been on EOL appliances, the potential to recycle pre-consumer (industrial) magnet scrap had been given less attention. Recycling of magnet swarf is already being practiced (Anonymous, 2015c). The consideration of this material as an input material for the indirect recycling process considered in this study is addressed in section 4.4.3.

The objective of this work was to give an estimate of global annual secondary REE supply from pre- and EOL magnet material in years 2020-30, considering eleven different application groups as sources for EOL magnets. 2020 was chosen as the starting year for which secondary REE supply is presented since the establishment of collection and recycling infrastructure is expected to take a few years. Effects of heavy REE (Dy, Tb) content reduction efforts are taken into account to reflect both expected changes in REE demand[7] for magnet applications and implications for the derived secondary supply. The potential supply from EOL magnet material was derived from the demand for magnets for the respective application groups, expected product lifetimes, expected collection efficiencies and losses during disassembly. A direct recycling route was assumed for magnets from hard disk drives (recycling of magnet material), and an indirect recycling route for magnets from other applications (extraction of

[77] For the purpose of this study, it is assumed that demand equals supply for both the Nd-Fe-B material required on the global market, and the rare earth quantities required for the production of the magnet material. The overall REE production figures are higher, since REE are also used in applications other than magnets.

REEs from magnets)[8]. The findings should be of interest to policy makers, and companies interested in recycling of Nd-Fe-B magnet scrap.

4.2 Methodological approach

4.2.1 Modelling of material flows

A dynamic material flow analysis was applied to estimate the global potential for secondary REE supply from Nd-Fe-B magnets. The focus was on sintered magnets which can be used as an input to the direct/indirect recycling routes described in Bast et al. (2015) and the direct route using hydrogen decrepitation (Sprecher et al., 2014b; Walachowicz et al., 2014). Sintered Nd-Fe-B magnets account for approximately 92-95% of current Nd-Fe-B production by mass.

The demand for rare earths for the production of Nd-Fe-B magnets was derived from information regarding the historic production and future demand for the applications which use them, such as wind turbine generators, electric and hybrid cars etc. (see 4.3 for a detailed description of Nd-Fe-B applications considered in this study). For most application groups, alternative technologies which do not rely on Nd-Fe-B magnets are available. Therefore, information on current and past market shares of applications which rely on Nd-Fe-B magnets, as well as future trends for the technologies with and without Nd-Fe-B magnets were taken into account where possible. For simplification, no differentiation was made between the demand and production of REE for use in Nd-Fe-B magnets; or between the demand and production of Nd-Fe-B magnets for use in different applications in a given year, i.e. it was assumed that no stockpiling or shortages would occur/ had occurred in the time period considered. In order to calculate the demand for Nd-Fe-B magnets, information on the magnet weights for the different applications was necessary. Based on the data for Nd-Fe-B magnet demand, the demand for REE used in these applications was calculated. For this purpose, information regarding the magnet compositions for different applications and their change over time and information on losses during magnet production were considered.

The information on historic and future Nd-Fe-B and derived REE demand was then used as a basis to calculate the potential for secondary REE supply from Nd-Fe-B magnets, taking into account both Nd-Fe-B magnets from EOL- appliances and production scrap. For this calculation, assumptions regarding the product lifetimes of the appliances, collection rates, the fraction of Nd-Fe-B magnets which can be extracted after collection, and material losses during the recycling process itself were required. This information was based on data from the literature, i.e. life cycle assessment or material flow analysis studies, and own estimates.

The material flow model which forms the basis for the quantification of sintered Nd-Fe-B demand and potential secondary supply is presented in section 4.2.1. Equations for annual demand calculations of individual rare earth elements, expressed in rare earth metal (REM) quantities, and the annual potential for secondary supply for individual REM from magnets extracted from EOL appliances are presented in section 4.2.2. The scenario approach taken to quantify the independent variables described in section 4.2.2 is presented in section 4.2.3. The numbers are derived from qualitative and quantitative information acquired through an extensive review of the literature, complemented by discussions with industry and own scenario assumptions (section 4.3).

[8] Both Nd-Fe-B material recycling (direct recycling) and rare earth extraction (indirect recycling) routes are currently being developed. For EOL magnet material from hard disk drives, a material recycling route has been trialled successfully. Direct recycling routes also have the potential for lower environmental impacts compared to indirect recycling routes. Direct recycling routes can, however, only be applied if the input material is sufficiently uniform in terms of its composition, as is the case for Nd-Fe-B magnets from hard disk drives, but not for most other Nd-Fe-B applications.

The focus of this work is on quantifying the potential secondary supply for Nd-Fe-B magnet material and individual REEs contained in the magnet material through a dynamic material flow analysis. The annual global demand for Nd-Fe-B magnets is derived from the demand for different Nd-Fe-B application groups in the same year. The potential for secondary supply of Nd-Fe-B magnets is derived from the volumes of different EOL appliances containing Nd-Fe-B magnets expected to become available in the respective year and production waste quantities derived from production of Nd-Fe-B magnets in the same time period (magnet material available for recycling, after subtraction of losses from collection and disassembly). The potential for secondary supply of individual REE is here defined as the amount (mass) of REM which can be supplied from secondary sources, including pre-and EOL magnet material, after subtraction of losses during collection, disassembly and recycling.

Both the material and element level are investigated. The demand and secondary material supply figures are used as a basis to derive the flow of the REE contained in the magnet material. The consideration of individual REE in the magnet material and the distinction between the different REE are relevant because of their unique properties, different mining routes, and different criticality levels. Furthermore, the REE composition in the magnets is related to their grade and suitability for use in different applications, with material cost implications. Assumptions are made for Nd-Fe-B/ REE losses occurring during Nd-Fe-B magnet production, EOL collection, disassembly and recycling.

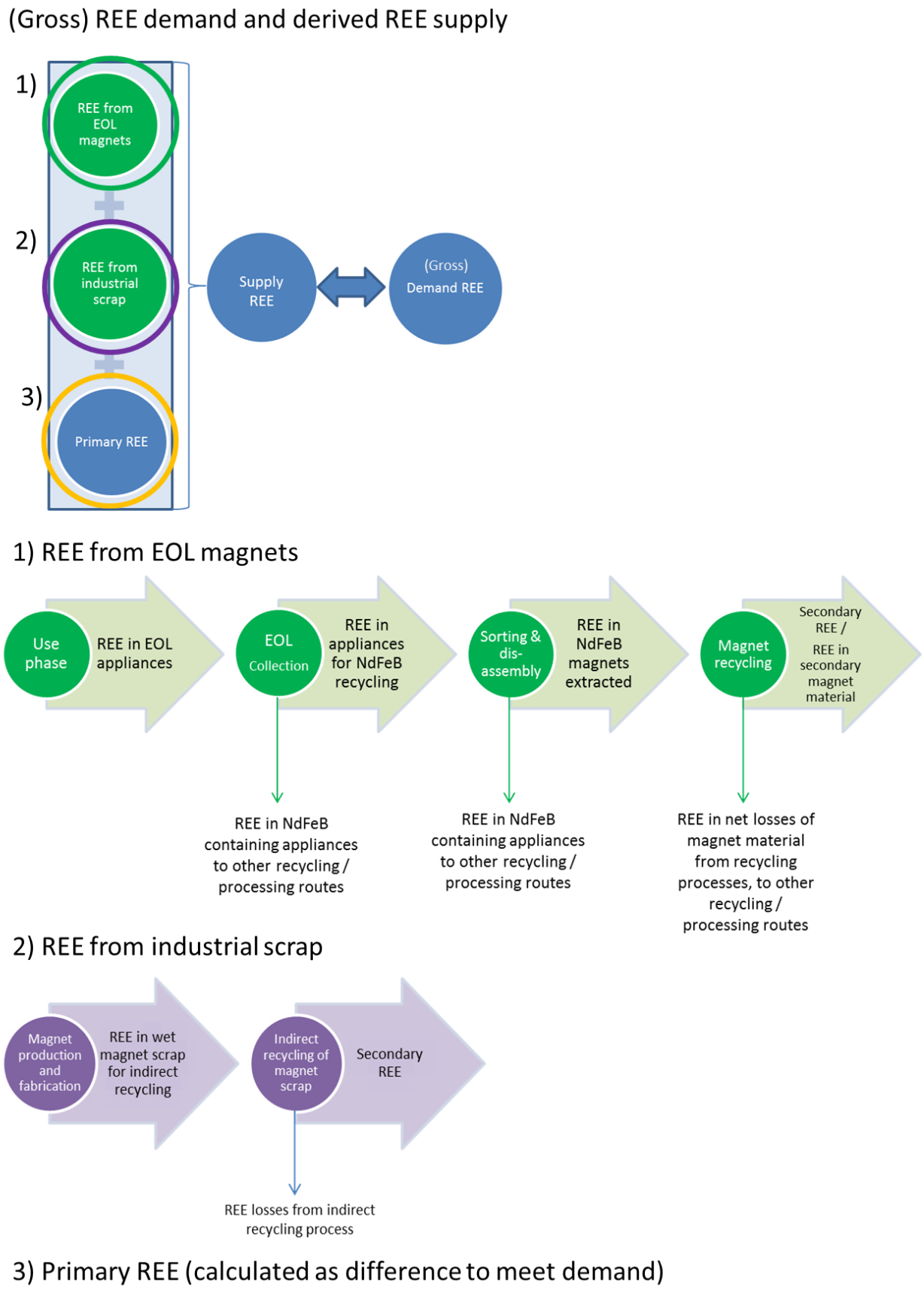

Figure 2: Illustration of model structure

The structure of the model is illustrated in Figure 2. The model assumes that for each year considered, the global supply (production) of REE for Nd-Fe-B magnets meets (gross) demand[9] for REE in Nd-Fe-B magnets, through a combination of Nd-Fe-B magnets from primary REE, secondary REE or secondary Nd-Fe-B material (see top left illustration of Figure 2). It is further assumed that magnets are demanded and supplied in the same year, and Nd-Fe-B material is recycled and made available as secondary material in the year it arises (no stockpiling). The contribution from primary production to the supply mix is the difference between the REE demand and the secondary supply. The composition of the production mix is modelled in two demand scenarios to reflect demand level uncertainties. Details on scenario assumptions are provided in section 4.2.3.

REE contained in magnets extracted from EOL appliances entering the secondary REE supply route each year is calculated from production quantities of Nd-Fe-B containing appliances, appliance lifetimes, magnet contents and compositions (see also 4.2.2, Equation 3)[10]. Losses then occur along the process route. A collection rate is assumed for each magnet-containing appliance group to estimate which fraction of the appliances is collected for recycling. Losses during sorting and disassembly may occur if the magnets are deeply embedded in the devices and cannot be easily extracted, are too small or not suited as input material. Once the magnets have been extracted, material losses occur at several processing stages during direct or indirect magnet recycling. The magnets which do not enter the recycling process are lost to other waste management routes, which can be other recycling routes not aimed at REE recovery. The distinction between alternative waste treatment routes (other than Nd-Fe-B recycling routes) is not of interest for this study. After subtraction of those losses, the flow represents the secondary REE input from EOL magnets, at the point where it enters the Nd-Fe-B magnet production process (see also 4.2.2, Equation 2).

According to the model assumptions, secondary REE from industrial waste are extracted from the wet scrap which is not suitable for direct internal material recycling. The quantities are estimated as a percentage of input material to the magnet production process. This type of scrap arises largely from cutting and grinding of the sintered magnets to the desired shapes, but also at other stages in the magnet production process. More details on scrap from magnet production can be found in section 4.3.2. It is assumed that the scrap material enters an indirect recycling process during which the REE are extracted from the material. Losses occur during this process.

The REE quantity which needs to be supplied from primary sources is the difference between REE demand and supply from secondary sources.

4.2.2 Demand calculation for REE used in Nd-Fe-B magnets, derived supply of REE from EOL Nd-Fe-B magnets and industrial scrap, potential recycling rates

Nd-Fe-B magnets are used in numerous applications with different specifications and magnet weights. The demand for individual REE used in Nd-Fe-B applications was calculated as the sum of the expected individual REE requirements for all magnet application groups, expressed in t REM (Equation 1). The bottom-up calculation of REE demand is described by the following equation:

$$D_{ij} = \sum_{k=1}^{n} g_j * p_j * m_j * c_{ij} * l_i \qquad \text{[Equation 1]}$$

- D_{ij} : demand for REE i in year j (sum of demand from all Nd-Fe-B application groups k, in tonnes REM)

[9] The gross REE demand represented in Fig. 2 corresponds to the gross demand for LREE and HREE shown in Figures 4 and 5, respectively.

[10] For simplification, it is assumed that the lifetime of the magnets is determined by the lifetime of the appliances containing them.

- g_j : demand quantities for appliances of Nd-Fe-B application groups k =1 - n, (n number of appliance groups) in year j (in numbers of appliances)
- p_j : percentages of appliances in groups k using Nd-Fe-B magnets in year j
- m_j : average masses of magnets in groups k in year j (in tonnes)
- c_{ij} : average weight percentages of REE i in year j in magnets of groups k
- l : efficiency factor <1 to account for average losses of REE in magnet production/fabrication of groups k

For some application groups, insufficient information was available to determine all the independent variables specified in Equation 1. Where this was the case, estimates for the total production of Nd-Fe-B magnets for use in this application group were taken from the literature and multiplied with l and c_{ij}. Details are provided in section 4.3.

The potential supply of secondary REE extracted from EOL magnets (neodymium and dysprosium, terbium and praseodymium) is derived from the REE demand figures, taking into account the product lifetimes for different Nd-Fe-B application groups and expected yields from collection, disassembly and recycling (Equation 2).The bottom-up REE supply from EOL magnet recycling is calculated as follows:

$$S_{\text{net } i,j} = \sum_{k=1}^{n} \mathbf{S_{gross}}_{i,j} * b * d * r \qquad \text{[Equation 2]}$$

- $S_{\text{net } i,j}$: net supply of REE i in year j from EOL magnet recycling from magnets from all application groups k (losses occurring during recycling deducted, in tonnes REM)
- $\mathbf{S_{gross}}_{i,j}$: gross supply of REE i in year j from EOL appliances from all groups k – (in tonnes REM, see Equation 3
- b : collection rates < 1 for magnets from EOL appliances k, constant for each group for all years considered (defined as "old scrap collection rate" in (UNEP, 2011))
- d : efficiency rates of disassembly <1 for EOL appliances k, constant rate for each group for all years considered
- r : efficiencies of REE extraction from EOL magnet in recycling process, <1, same efficiency for different REE i assumed, constant over time period considered[11] (defined as "recycling process efficiency rate" in (UNEP, 2011))

$$\mathbf{S_{gross}}_{i,j,k} = \sum_{l=base\ year}^{j-1} \mathbf{D}_{i,k} * p_{j,l,k} \qquad \text{[Equation 3]}$$

The results from this equation for all groups k are used to form the vector Sgross i, j for all groups k, (see Equation 2).

- $\mathbf{S_{gross}}_{i,j,k}$: gross supply of REE i from EOL magnets arising in year j produced for use in group k applications in years l , in tonnes REM)
- D_{ik}: (historic) demand for REE_i in all years *l* for applications in group k (in tonnes REM)

[11] For the direct recycling process for the hard disk drives, the losses in the recycling process refer to the magnetic material recycling, rather than individual REE extraction. ***r*** then stands for efficiency of material recycling.

- $p_{k,l,j}$: vector, probabilities of magnet containing appliances from groups k produced (demanded) in year *l* to become available for recycling in year *j,* assuming a Gaussian probability distribution of lifetimes with

$$p = f(m) = \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}*\left(\frac{m-\mu}{\sigma}\right)^2} \quad \text{[Equation 4]}$$

with p: probability of magnet produced in year l to reach EOL in year j (scalar)

with m=j-l, (time appliance has been in use, age of the appliance)

with average lifetime μ and standard deviation σ

Equ. 4 represents a Gaussian probability distribution[12].

$$I_{net\ ij} = D_{ij} * o * r \quad \text{[Equation 5]}$$

with $I_{net\ i,j}$: supply of REE i extracted from industrial scrap arising in year j

with o : factor >0<1 to account for material losses during magnet production /fabrication (to calculate scrap quantities arising)

with r : efficiencies of REE extraction - see above, same for industrial scrap and EOL magnet material.

$$\text{potential RIR}_{ij} = (S_{net\ i,j} + I_{net\ ij}) / D_{ij} \quad \text{[Equation 6]}$$

with potential RIR ij : (average) recycled content in the (global) production flow of REE i in year j, in line with the "Recycling Input Rate" defined in UNEP (2011). For this study, the equation refers specifically to the percentage of demand for REE i in year j for use in Nd-Fe-B magnet production which can be met by REE i supplied from secondary sources (according to scenario estimates).

4.2.3 Quantification of the potential for secondary REE supply from EOL magnets and production waste via a scenario approach

EOL magnet quantities derived from Nd-Fe-B demand

To reflect uncertainties in the development of the Nd-Fe-B magnet market, derived from the demand of the respective applications, a scenario approach is adopted to illustrate possible future market developments. Since a complete and reliable dataset for historic Nd-Fe-B demand in different application groups was not available, the uncertainties of historic demand figures were also addressed by the same scenarios. The scenarios differ in their levels of Nd-Fe-B demand and resulting REE demand and in terms of derived potential for secondary Nd-Fe-B /REE supply. Based on the calculation method outlined in 4.2.2, Equation 1, two Nd-Fe-B demand scenarios were constructed, starting from the respective base year and ending in 2030:

1) *Low Nd-Fe-B demand scenario*, based on lower-end demand estimates for individual Nd-Fe-B magnet application groups, with derived demand scenarios for individual REEs (Nd, Dy, Pr, Tb), considering only the fraction of the REE demanded for use in Nd-Fe-B magnets (i.e. Nd, Tb, Dy, Pr used in applications other than sintered Nd-Fe-B magnets are not taken into account). This scenario assumes moderate growth in demand for applications and components, and **slower** progress in heavy REE (Dy, Tb) content reduction in the magnets.

[12] See e.g. https://www.physics.ohio-state.edu/~gan/teaching/spring04/Chapter3.pdf or https://en.wikipedia.org/wiki/Gaussian function

2) *High Nd-Fe-B demand scenario*, based on higher-end demand estimates for individual Nd-Fe-B magnet application groups, with derived demand scenarios for REEs Nd, Dy, Pr, Tb, considering the fraction of the REE demanded for use in Nd-Fe-B magnets. This scenario considers higher growth rates in demand for applications and components, and **faster** progress in heavy REM (Dy, Tb) content reduction in the magnets.

The quantification of the material flows was based on a review of the literature conducted to obtain an understanding of the markets for the Nd-Fe-B containing application groups. Quantitative and qualitative information was obtained to model the market trends at product/component and magnet material level and derive Nd-Fe-B /REE demand scenarios.

Historic market information on Nd-Fe-B magnet containing appliances was included, starting from a "base year", to determine quantities of material available for recycling from EOL magnets, based on the expected product lifetimes (and probability distribution) to account for all appliances reaching EOL in years 2020-30. The data obtained from scientific publications, company reports and other sources was complemented by discussions with experts from industry and research. For each demand scenario, the potential for secondary supply of Nd-Fe-B material and REE from EOL magnets was calculated according to [Equation 2.

Production waste

The potential for secondary supply from pre-consumer magnet scrap was quantified in a top-down approach based on information on the process material efficiency in sintered Nd-Fe-B magnet production, and Nd-Fe-B production quantities. The supply was calculated for years 2020 to 2030. The information which formed the basis for the assumptions was obtained from interviews with industry experts and literature data. The data is presented for the respective years in which the material arises.

4.3 Overview of applications and key assumptions

4.3.1 Nd-Fe-B magnets used in different application groups, current technology trends

Electric two-wheelers

Electric two-wheelers are powered by a combination of manpower and electric power, or electric power only. E-bicycles (pedal-assisted or throttle controlled e-bikes), scooters and e-motorbikes are included in this application group. E-bicycles dominate in numbers in the electric two-wheeler group (around 86% of vehicles in 2015). According to one source, the distinction between throttle-controlled e-bikes and scooters is based on whether they can be pedaled by the rider (INSG, 2014). The largest market for e-bikes is China, with an approximate 90% market share by volume (INSG, 2014). The global market is expected to see substantial growth in the next years. E-bike motors constitute an important application of Nd-Fe-B magnets, currently accountable for around 8% of global Nd-Fe-B demand (Lucas et al., 2015). In accordance with the expectance of an expanding e-bike market, the demand for Nd-Fe-B magnets for use in e-bikes is expected to grow (Bast et al., 2015; Binnemans et al., 2013a; Shaw and Constantinides, 2012). REE free e-bike motors have been developed (Honkura, 2013), but details on or evidence of their current use could not be found. It is assumed that almost all e-bikes produced today use sintered Nd-Fe-B-magnet based motors – based on findings by Schüler et al. (2015), who conducted expert interviews to answer this question.

Air conditioners

Permanent magnet motors with Nd-Fe-B magnets are used in compressor motors of some air conditioners (AC) (Hitachi, 2011). Fan motors sometimes contain Nd-Fe-B magnets (Constantinides, 2014b; Grieb, 2014), but are mostly ferrite-based (Anonymous, 2015a). The global demand is growing for both commercial and residential ACs. Gloel et al. (2015) provide details on different air conditioner types. Growth rates around 5% are expected for the next years (PR Newswire, 2015a). Approximately 80% of ACs are manufactured in China (2013 figures) (Yu, 2014). The largest AC markets are China, Japan and USA, with largest growing markets in Asia, Africa and South America (Holley, 2014; Yu, 2014). Efficiency standards for air-conditioning units are being raised to achieve GHG emission targets (Mikami, 2012; Yu, 2014), with efficient Nd-Fe-B-based compressors expected to support this transition (Frontier Rare Earths, 2012; Minowa, 2008).

The global demand for Nd-Fe-B magnets used in air-conditioning systems is expected to increase (Benecki, 2013; Frontier Rare Earths, 2012; Shaw and Constantinides, 2012); and an increase in Nd-Fe-B demand associated with the growing market for inverter air conditioners in China is expected (Frontier Rare Earths, 2012; Kesheng Magnet, 2013; Research in China, 2011). However, based on the information found in the literature, it is difficult to derive assumptions for a bottom-up quantification of Nd-Fe-B magnets used in air conditioners. Apart from the lack of reliable information on the market share of Nd-Fe-B-based air-conditioning systems, the difficulties arise from the large variation in magnet weights per air conditioning unit. Values for magnet weights of Nd-Fe-B magnets in air conditioners are between 100g-500g for domestic and 250-300kg for industrial air conditioners, (Bast et al., 2015; Habib et al., 2014; Isfatuni et al., 2013). The collection and recycling of magnets from air conditioners is already being practiced in Japan (Hitachi Ltd., 2010; Mitsubishi Electric, 2014b).

Traction motors hybrid and electric cars ((H)EVs)

The global demand for passenger cars is increasing, driven by the demand in new markets, e.g. India and China. Although they only contribute a small fraction of global passenger cars on the road today, sales of hybrid and electric vehicles have grown in the past years (EVI, 2015) and are expected to grow until 2030, with different levels of global electric vehicle uptake projected (Kühn et al., 2014; Siemens, 2014b). It has been suggested that the shift towards electric and hybrid vehicles could make EV traction motors the main application for REE by 2050 (Habib and Wenzel, 2014). Hybrid cars are currently dominating the automotive hybrid and electric market (Kühn et al., 2014).

Direct current (DC) brushless rare earth permanent magnet (REPM) motors are standard for hybrids and plug-in hybrids (Burwell et al., 2013; Rippel, 2007). Electric cars use PM (permanent magnet) or induction motors. Mitsubishi, Toyota, Nissan and Chevrolet's models run with permanent magnet motors (Chevrolet, 2015; Mitsubishi Electric, 2015; Nakada et al., 2014; Toyota Global, 2015), whereas Tesla BEVs use induction motors, based on copper rotors (Green Car Congress, 2013; Widmer et al., 2015). Traction motors for hybrid and electric vehicles are amongst the Nd-Fe-B applications which require the highest HREE contents (Binnemans et al., 2013a), due to high operating temperatures. However, considerable research efforts are being conducted at material and component level.

Operating temperatures around 150°C, which might be reached in today's traction motors of hybrid or electric cars (Galioto et al., 2015), require HREE contents higher than those of other Nd-Fe-B applications to prevent demagnetization. To some extent, the operating temperatures can be altered by changing the motor design: a few years ago, specifications for Nd-Fe-B magnets in hybrid cars were designed for operating temperatures of 180°C – see Gutfleisch et al. (2011). REE free motors for hybrid cars are currently at research stage – see e.g. Chiba et al. (2015). Research regarding new magnet production methods focusses on microstructural changes, with the aim to enhance magnetic prop-

erties and reduce HREE content; e.g. via a more even distribution of the Nd-rich phase or a reduction in grain size (Brown et al., 2014; Goto et al., 2012). Different grain boundary diffusion methods are already being successfully implemented, allowing for a significant reduction in HREE content. Some electric/hybrid car manufacturers report HREE reduction efforts for the magnets used in their traction motors (Chevrolet, 2015; Molycorp, 2013; Nakada et al., 2014). The adoption of the grain boundary diffusion technologies is likely to spread in coming years (Anonymous, 2015d), allowing a further reduction in global heavy REE use.

MRI scanners

MRI scanners can be based on permanent magnets, superconducting magnets or electromagnets, with superconducting magnets being the most popular technology in use today. The market is currently dominated by high-field MRI scanners which use superconducting magnet technology (Markets and Markets, 2015). Permanent magnet based MRI constitute the second most popular technology (Gupta and Kumar, 2014). They are used in smaller, open MRI scanners and generate lower field strengths than superconducting MRI scanners (up to 0.35 Tesla) (Cosmus and Parizh, 2011; Zepf, 2015). Today, Hitachi is the global market leader in open MRI systems, with two thirds of their installed capacity based on permanent magnet technology (Hitachi, 2015b, 2015c). In their latest business report, they report declining sales for permanent magnet MRIs (Hitachi Medical Corporation, 2013). Values for magnet weights of Nd-Fe-B magnets in MRI scanners found in the literature are between 700 and 3000 kg per device (Bast et al., 2015; Talens Peiró et al., 2013), making MRI scanners an interesting material source for recycling in principle.

Overall, the information on Nd-Fe-B containing MRI scanners or low-field MRI scanners found in the literature was non-conclusive. Details on the estimates found in the literature are provided in the Annex A2. The uncertainties regarding the numbers of MRI scanners based on Nd-Fe-B magnets are reflected in different low- and high Nd-Fe-B demand scenarios.

Generators used in wind turbines

Geared doubly-fed induction generators are currently the most common wind turbine generator type on the market (Blaabjerg and Ma, 2013). Larger difficult-to-access offshore turbines benefit from the gearless permanent magnet (gearless PM) drives since they require less maintenance. Lower speed turbines suitable for use in areas with lower wind speeds; also rely on PM direct drive technology (Lacal-Arántegui, 2014; USDOE, 2015).

Global annual installations of wind power capacity are expected to grow until 2030 (Lacal-Arántegui, 2014). PM (Nd-Fe-B) generators and high temperature superconductor generators are seen as the two promising future technologies for higher performance generators (Lacal-Arántegui, 2015); with the latter not as advanced in their development. As with magnets used in (H)EV traction motors, manufacturers are reducing the Dy content in the magnets in an effort to reduce risks associated with REE price volatility. Siemens is aiming to completely eliminate Dy from the magnets used in their wind turbines by 2017 (DERA, 2014; Metalevents, 2014). Furthermore, future development aims at the reduction of magnet weights per MW installed via the improvement of magnetic densities (Lacal-Arántegui, 2015).

Uncertainties regarding the recycling potentials from EOL Nd-Fe-B magnets used in wind turbine applications arise from projections regarding the share of new installations with REPM magnets in the next 15 years and from lack of knowledge on the actual lifetimes of the turbines (extent of generator / turbine reuse at EOL). Whilst the reuse of magnets from wind turbines is considered unlikely (Zero Waste Scotland, 2014), the reuse of decommissioned turbines is practiced for wind turbines from the EU, which are generally sold on the international market (Lacal-Arántegui, 2014). The composition of

the magnets is being changed to contain less dysprosium, with implication for the potential supply of secondary HREE. However, this has been reported by a single turbine manufacturer. Chinese manufacturers may not be equally motivated to reduce REE contents. The global average will significantly shift if the new designs are adopted by other manufacturers.

Hard disk drives

Nd-Fe-B magnets are used in hard disk drive (HDD) motors (voice coil actuators) to move read/write heads (Constantinides, 2012). The global demand for data storage is rapidly increasing. Presently, HDDs are the most common storage solution, but the use of Nd-Fe-B-free solid state disks (SSDs) has seen an exponential increase since 2010 (Sprecher et al., 2014a). HDDs applications for traditional consumer applications (desktops, laptops) are in decline, but the decline could be compensated to some degree by the increased use in the expanding segments, namely enterprise and gaming applications (Businesswire, 2015; Toshiba, 2014; Western Digital, 2014). Besides a small compositional variety, HDDs offer the benefit of being available in larger quantities than newer Nd-Fe-B applications, and could serve as a secondary REE source in the near future.

Acoustic transducers

Electro-acoustic transducers either convert electricity to sound, or sound into electric signals. Common applications include speakers, headphones and microphones. Other applications include material property characterization tools and echo sound tools used in fishing or for the detection of pipe leaks. 35% of Nd-Fe-B demand was for use in audio systems in 2009, with lower percentages around 7% in developed countries (Du and Graedel, 2011). Speakers are found in PCs, notebooks, TVs, cars, and other audio systems. In larger speakers, Nd-Fe-B magnet weights are around 100-300g, based on information taken from a product specification (Eminence, 2015). Nd-Fe-B magnets used in small speakers used in mobile phones and mobile phone headphones weigh around 0.3g (Zepf, 2013). 2.5 g of Nd-Fe-B magnet material are used in speakers of notebooks (Buchert et al., 2012).

According to a Chinese magnet manufacturer, ferrite is the most common magnet type used in speakers (EukeMag, 2014). It is likely that Nd-Fe-B magnets are widely used in small speakers for mobile phones and notebooks, tablets and headphones, but detailed information on the percentages of speakers with Nd-Fe-B magnets was not available in the literature. According to Lucas et al. (2015), the market is not expected to grow significantly in future due to the replacements of magnets by piezoelectric transducers. Piezoelectric speakers can be built even smaller than REPM based speakers, and consume around half the power (BeStar Acoustics, 2012; ECN, 2012; Onishi et al., 2010). They are being mass-produced for the use in mobile phones, tablets and other mobile devices (Murata, 2011). Details on market penetration could not be found.

Magnetic separators

Magnetic separators allow for effective removal of metal contamination from agricultural products, coal, and chemicals, during mineral processing, manufacturing and recycling processes (Lucas et al., 2015). Apart from ensuring a clean material, they help protect the equipment (conveyor belts etc.) from being damaged by metal pieces (Wei, 2009). Rare-earth permanent magnet separators became popular in the 1990s (Fuerstenau and Han, 2003). Nd-Fe-B magnets are used for the separation of wet and dry materials, normally for the extraction of smaller particles, while larger ferrous pieces are extracted with electromagnets. The demand for Nd-Fe-B magnets used in magnetic separation is expected to “increase steadily” (Prysmag, 2015). Growth is expected for the moderate field strength separators used in mining, and mainly driven by the development of the mining industries in the Asia-Pacific region (FMI, 2015; Transparency Market Research, 2015). Average weights for Nd-Fe-B magnets used in

separators or numbers for units produced could not be obtained. Large magnetic separators are manufactured based on the bespoke needs of the clients.

Other generators (excl. wind turbine generators)

Nd-Fe-B applications related to power generation include power generators other than wind turbines. Nd-Fe-B magnets are used in automotive alternators (Constantinides, 2015) and bicycle dynamos (Molycorp, 2013). REPM generators are used in small hydropower plants, tidal or wave power plants and other renewable energy applications (Alibaba, 2015; Binder and Schneider, 2005; Ikäheimo, 2009; Shaw and Constantinides, 2012; Smith Stegen, 2015). High-speed permanent magnet generators are used in microturbines – small gearless combustion turbines which are suited to generate the energy off-grid, or as part of a power network (Huynh et al., 2009). REPM are also used in portable generators, which are enjoying increasing popularity in the Asian-Pacific region, and for which an annual growth of 8% is predicted until 2019 (TechNavio, 2015). Constantinides (2012) estimated the demand for Nd-Fe-B magnets for use in generators to roughly halve between 2010 and 2015. The weights of magnets used in generator applications vary greatly. A 300kW turbine for a small hydropower plant uses 72kg of REE magnets (Binder and Schneider, 2005), whilst the total weight of rare-earth magnet based dynamos can be as low as 52g (Velogical Engineering, 2015).

Other motors

Motors used in industry, cars and other applications now constitute the largest application group for Nd-Fe-B magnets at around 25% by volume (Constantinides, 2014b)[13]. The demand for magnets in this group is growing exponentially and has been the cause for the rapid increase in dysprosium demand in years 2000-10 (Mikami, 2012). Electric motors are responsible for around 45% of the global electricity consumption (Waide and Brunner, 2011), which illustrates the need for efficient motors such as rare-earth permanent magnet (REPM) motors. New energy performance standards and rising electricity prices are expected to drive the production of energy efficient motors (Buchert et al., 2013; GlobeNewswire, 2015).

Industrial applications for which PM motors are suitable include adjustable speed pumps, fans, extruders, conveyers, crane and hoist systems, winders and printing presses (USDOE, 2014). Factory automation, including robotics and material handling, is currently the largest sector by revenue for PM motors (PR Newswire, 2015b). The majority of PM electrical machines (motors, generators) is Nd-Fe-B-based (DrivesNControls, 2015; Eriksson, 2014). Globally, the use of Nd-Fe-B magnets in PM motor applications is predicted to grow at an annual rate of 10.8% from 2014 until 2020 (PR Newswire, 2015b).

Automotive applications of sintered Nd-Fe-B magnets other than traction motors in electric/ hybrid cars include motors for electric power steering (EPS), automated manual transmission motors, starter motors etc. and other small automotive motors (Constantinides, 2014a; Hitachi, 2015a; Shin-Etsu, 2015). There is a tendency towards “electrification”, resulting in an increasing number of electric motors, especially in high-end cars. Belt-driven components (connected to the main drive motors via a belt), for example, are being replaced by electronically driven ones to increase energy efficiency (Arnold Magnetic Technologies, 2014). EPS and automotive transmission motors are increasingly adopted in new vehicles due to fuel efficiency improvements associated with the automation. There can be up to 100 motors in high-end cars, most of which, however, are DC brush motors with ferrite magnets (Hitachi, 2015a), with an estimated average 250g of Nd-Fe-B magnets per standard car, mainly used in motors

[13]This percentage excludes the motor applications which are addressed as separate categories in this paper (HDD, Electric Two-Wheelers, HEV/EV and air conditioners) in this paper – if included, motors account for more than half of NdFeB applications by mass.

and sensors (Shaw and Constantinides, 2012). Some ferrite-based automotive accessory motors are being replaced with bonded Nd-Fe-B magnet motors which are smaller and lighter (Honkura, 2013; Magnequench, 2009; Sheth, 2011). The use of bonded magnets for automotive applications, such as fuel pumps and ABS motors, is increasing (Pati et al., 2013). Research efforts undertaken to reduce the use of (heavy) REEs include the development of bonded magnets motors with no dysprosium content (Honkura, 2013).

Other Nd-Fe-B motor applications include motors used in buildings and other infrastructure (e.g. pumps, fans, office automation, elevators and escalators and home appliances). Home appliances like refrigerators, vacuum cleaners and washing machines are available with efficient rare earth permanent magnet (REPM) motors. The motors are advantageous in terms of noise and energy efficiency. Globally, 250,000 elevators and escalators are installed per year (Zepf, 2015) citing (IMU-Institut, 2007). In Europe, PM synchronous motors are becoming the leading technology in this application field, with an increased share of rare-earth magnet based motors (ISR, 2010).

Pumps used in central heating systems offer large energy saving opportunities, with inverter PM motors constituting one of the key factors driving this improvement (Waide and Brunner, 2011). The use of efficient pumps in heating systems is now mandatory in the EU, and pump manufacturers are increasingly building pumps with efficient REPM motors (Anonymous, 2015f; Sims, 2015). Both sintered and bonded Nd-Fe-B magnets are used in pump motors, with typical magnet weights of 30-200g per pump, depending on pump motor size (Anonymous, 2015f). Around 32 million circulation pumps are produced worldwide annually for use in private homes, commercial buildings and industry etc. (Grundfos, 2014). Not all of these pumps contain PM motors, see e.g. (Meza, 2014).

Other Nd-Fe-B applications

Due to the tremendous diversity of Nd-Fe-B uses, many applications could not be investigated in detail for the purpose of this study. They include sensors, torque coupled drives, hysteresis clutches, energy storage systems, gauges, brakes, relays and switches, other transport applications (trains, magnetic levitation), etc.

4.3.2 Pre-consumer scrap

Pre-consumer magnet scrap arises at various stages in the manufacturing process (Anonymous, 2015d; Lyman and Palmer, 1993)[14]. The most relevant waste streams in terms of mass are dry magnet material arising from cutting block magnets into shape or off-quality magnets, which can be suitable as an input for direct recycling processes (e.g. remelting), and wet swarf from magnet finishing processes, only suitable for indirect recycling processes, since the material is contaminated and partly oxidized (Bast et al., 2015; Tanaka et al., 2013). Around 20- 30% of the starting material is lost during the magnet production process as wet swarf from magnet finishing processes (Anonymous, 2015b; Constantinides, 2015; Tanaka et al., 2013). Losses are lower for magnets pressed to shape before sintering and higher for block magnets which are cut to shape. For magnets cut to shape, the percentage of the material lost in this process depends on the surface-to-mass ratio of the magnets, and is hence larger for smaller magnets. An additional (gross) 10% of the initial alloy material becomes solid magnet waste, arising from block cutting and off-quality magnets (i.e. magnets which do not pass the quality tests). Expert opinions differed on the extent of recycling for manufacturing scrap, and information on the specific processes currently employed for the recycling of the production waste were not available.

[14] In bonded/ hot-pressed magnet production, scrap arises from alloy melting, discarded ribbon material or discarded finished magnets. Powder metallurgy processes produce waste from grinding, discarded sintered and unsintered (green compact) magnet pieces.

Clean hard scrap is internally recycled. The uncoated dry magnet material waste is collected according to composition and recirculated via direct recycling route, ideally to be used internally in products of the same composition. Most of the solid waste (ca. 90%) can be used for internal recycling (Anonymous, 2015d). It is mixed with the alloy material (Tanaka et al., 2013). Off-quality magnets which have already been coated are usually processed in indirect recycling routes (Anonymous, 2015b). Nickel coatings, for example, are detrimental to magnetic properties (Liu and Chinnasamy, 2012). Direct internal recycling of solid magnet material has the advantage of a known composition of the material for recycling; both the sources of contamination and quantities arising are predictable, and the material is promptly available for internal reprocessing. However, some property losses are experienced, limiting the percentage of hard scrap in the material (Anonymous, 2015d; Walachowicz et al., 2014).

It is likely that indirect recycling routes are used to extract the REEs from the wet scrap. Based on the information obtained, there is a market for sintered Nd-Fe-B manufacturing scrap, and it is possible that the potential secondary supply from sintered Nd-Fe-B manufacturing scrap is already being utilized to a large degree, and will be utilized in the time period 2020-30. Indirect recycling is more complex than direct recycling, but can produce pure REE, which can be sold on the market. It is expected that the processes applied for indirect recycling of REEs from magnet swarf are similar to that starting from the (concentrated) ore; however, the REE concentration in the starting material is higher. Some magnet manufacturers export the wet swarf (Bast et al., 2015) and other material not suitable for direct internal recycling. Information on the specific processes conducted is usually undisclosed (Anonymous, 2015b, 2015c; Tanaka et al., 2013). Indirect recycling of magnet scrap is already practiced in China and economically viable (Anonymous, 2015b; ERECON, 2015). According to one expert opinion, the potential for material efficiency optimization in magnet production is already well utilized, implying that Nd-Fe-B process waste is not commonly landfilled. Hitachi recycle 95% of the scrap from their magnet manufacturing process (Hitachi, 2014a). Kingsnorth (2014a) state that pre-consumer magnet swarf recycling is now starting to become economically viable. Swarf stockpiles are estimated to contain 10-50 kt REO, depending on the consulted source (ERECON, 2015; Kingsnorth, 2014a).

It has been suggested that wet processing waste could be used as a base load for indirect recycling processes to be set up for EOL material magnets to alleviate the current problem of small quantities of EOL magnets available for recycling and insufficient feedstock in the near future (Bast et al., 2015). This type of waste is suitable as an input material to the indirect recycling route investigated by Bast et al. (2015), and constitutes the most relevant input in terms of feedstock quantities arising in the near future (see section 4.4.3). This suggests that the swarf should be considered in the quantification of potential secondary supply to be used as an input to the indirect recycling route. There is some indication that the recycling processes currently employed may involve a large number of processing steps, and may therefore be associated with higher environmental impacts than other (more optimized) indirect recycling routes. However, due to the lack of information on the exact processing routes which are currently applied, the differences between the suggested and the currently practiced routes cannot be detailed in this paper.

4.3.3 Key assumptions

An overview of key scenario assumptions is provided in this section. Background information compiled to derive these assumptions can be found in Annex A1. The grouping of Nd-Fe-B magnet applications was based on Constantinides (2014b), who provided an estimate for Nd-Fe-B demand by application group for the years 2010 and 2015.

Assumptions for demand calculations

Demand for individual REE was calculated according to Equation 1 (section 4.2.2). The variables in the equation were estimated by compiling information on current use and demand growth rates for Nd-Fe-B used in different application groups, and historic production rates relevant to the quantification of EOL quantities arising. Furthermore, for each group, information on the fraction of applications which contains Nd-Fe-B magnets, size and composition of magnets was used to come up with the values for the variables. This information was compiled from qualitative and quantitative information found in the literature – see Annex A1 for details and literature references.

The demand growth rates for years 2020-2030 have been grouped into 5 categories from *"declining"* to *"very high growth"*.

Table 1: Nd-Fe-B demand growth rates by application group, years 2020-30

	Average annual demand growth rates for NdFeB demand by application group 2020-30 - low NdFeB demand scenario	Average annual demand growth rates for NdFeB demand by application group 2020-30 - high NdFeB demand scenario
Electric two-wheelers	3%	7%
Air Conditioners	9%	10%
(H)EVs	5%	20%
MRI Scanners	-8%	-2%
Wind Generators	14%	26%
HDDs	-3%	2%
Accoustic transducers	-2%	3%
Separators	1%	4%
Other generators	0%	3%
Other motors	10%	12%
Others	8%	12%

	< -3% (declining)
	-3 to +3% (+/- stable)
	3% to 7% (low growth)
	7% to 10% (high growth)
	>10% (very high growth)

As discussed in 4.2.1, it is assumed that the production and sale of Nd-Fe-B magnets happen in the same year, i.e. the demand quantities for Nd-Fe-B applications in the respective year are directly linked to the REE demand figures, with no time delay. The demand for REE for use in Nd-Fe-B magnet production was derived from the content of REE in the Nd-Fe-B magnet material demanded in the respective year. A percentage was added to account for REE losses during magnet production (20% of REE (in REM weight %) in starting material).

A total REE content of 31% by weight is assumed. Nd and Pr are the two light REE (LREE) presently used in Nd-Fe-B magnet production. Up to 25% of Nd required can be replaced by Pr without significant magnetic property losses in some magnets. Regarding HREE, Dy can be replaced by Tb, which allows for better magnetic properties. This is currently uncommon because the additional cost of Tb exceeds the additional „benefit" of using the more effective HREE (Anonymous, 2015b, 2015e). Tb is used in compact fluorescent lightbulbs, which may be gradually replaced by light emitting diodes in future, and for which a recycling process is now available – see e.g. Machacek (2015). It has been suggested that the increased use of LEDs could free up some terbium for the use in Nd-Fe-B magnets in future (Binnemans and Jones, 2015). An average LREE mix of 17% Pr, 83% Nd, and an average HREE mix of 92% Dy, 8% Tb were assumed, based on the demand for the elements for use in Nd-Fe-B magnets reported in EC (2014). The average HREE content in the Nd-Fe-B magnet material varies between application groups and is assumed to decrease from an average content of 4%/3.7% by weight in 2015 to 2.5%/1.4% by weight in 2030 for the low and high Nd-Fe-B demand scenario, respectively.

Assumptions for recycling routes and secondary supply calculations

In order to estimate the potential for secondary supply from both EOL magnets and industrial scrap from Nd-Fe-B production, assumptions for the supply of secondary materials were necessary.

Assumptions regarding recycling routes

Direct and indirect Nd-Fe-B recycling routes are distinguished. In direct recycling, the magnet material is recovered. In indirect recycling routes, rare earths are extracted. Direct recycling is feasible for sintered magnets from hard disk drives due to small compositional changes over the years for those magnets (Binnemans et al., 2013a). For example, this can be achieved through a hydrogen decrepitation, milling and resintering route (Sprecher et al., 2014b; Walton). Sintered Nd-Fe-B magnets from voice coil motors (VCM) are used as input material for this route. Direct recycling avoids the complex extraction of REEs from the magnet material. Small percentages of Nd hydride additions are necessary to avoid downcycling, i.e. losses in magnet performance caused by Nd oxidation and evaporation (Zakotnik et al., 2009). VCM magnets from HDD are already being collected, extracted and recycled in Japan (Hitachi, 2014b), albeit through an indirect recycling route (Hitachi Ltd., 2013). For the scenarios, it was assumed that hard disk drives, contrary to EOL magnets from other appliances and industrial scrap, are processed in a direct recycling route (hydrogen decrepitation and resintering).

Indirect recycling for rare earths from magnets has been trialed, e.g. for EOL Nd-Fe-B magnets from motors of hybrid cars, and is transferrable to other magnet applications (Bast et al., 2015; Walachowicz et al., 2014). EOL magnets from all application groups presented in 4.3.1, as well as pre-consumer scrap, were assumed to be processed in an indirect recycling route (Route 3, described in Walachowicz et al. (2014). Magnets are extracted from motors, demagnetized and milled. The powder is leached, exogens are precipitated and rare earths are separated in a solvent extraction process.

For this study, the assumptions regarding the chosen recycling routes are relevant regarding the process-specific material losses during recycling, which are detailed in the following paragraph.

Scenario assumptions secondary supply

Supply of REE from EOL magnet recycling was estimated from (historic) Nd-Fe-B use in different application groups, average product lifetimes, with normal distribution of lifetime probabilities, and material losses occurring during collection, disassembly and recycling operations assumed (Table 2). The losses occur when material is landfilled or incinerated, or collected for other recycling routes, which do not recover REE or Nd-Fe-B material (e.g. steel recycling). Estimates on product lifetimes and collection rates were taken from literature sources or communicated during expert interviews – see Annex A1 for details. Losses during disassembly are mainly based on own estimates. Estimates take into account factors such as magnet weights per appliance, the fraction of bonded magnets not suitable as an input to the recycling processes, and information from existing collection schemes, disassembly or recycling trials where available. For the calculation of potential secondary REM supply, as a rough estimate, it was assumed that 10% of Nd-Fe-B material / REE is lost in the direct recycling route applied for HDD recycling, and 8% of the REE material is lost in the indirect recycling routes applied to EOL Nd-Fe-B material from other applications (Bast et al., 2015; Sprecher et al., 2014b), starting from the point at which the magnets have been extracted from the appliances. The distinction between alternative waste treatment routes (other than Nd-Fe-B recycling routes) is not of interest for this study. Post-consumer (EOL) magnets are expected to become available to enter the recycling route or other waste treatment route in the year the appliance reaches EOL, i.e. the option to stockpile EOL material for future recycling was not considered. As a consequence, the starting year from which Nd-Fe-B produc-

tion was taken into account for consideration in the secondary supply scenarios varied by application, depending on the typical product lifetimes.

Furthermore, the data quality differed between application groups. A bottom-up calculation was not possible for all application groups – see the Annex A1 for details.

Quantities of secondary REE supply were estimated in a top-down approach, assuming that 20% of input material in magnet production becomes scrap not suitable for direct internal recycling. The composition of this production scrap is in accordance with that of the production mix in the respective year.

Table 2: Key assumptions REE supply from EOL Nd-Fe-B magnets

	Product lifetime (years)					
	Mean	Standard Deviation	Collection Rate	Efficiency Rate Disassembly	Efficiency Rate Recycling	Overall REE extraction efficiency
Electric Two-Wheelers	5	1.25	80%	90%	92%	66%
Air Conditioners	12	3	60%	90%	92%	50%
(H)EV	15	3.75	90%	90%	92%	75%
MRI Scanners	12	3	80%	90%	92%	66%
Wind Generators	22	5.5	90%	90%	92%	75%
HDD	10 / 6	2.5 / 1.5	60%	60%	90%	32%
Acoustic Transducers	8	2	50%	50%	92%	23%
Separators	10	2.5	80%	80%	92%	59%
Other generators	20	5	80%	90%	92%	66%
Other motors	13	3.25	80%	40%	92%	29%
Others	**10**	**2.5**	**30%**	**10%**	**92%**	**3%**

4.4 Scenario Results

4.4.1 Demand for Nd-Fe-B magnets and derived REE demand

Nd-Fe-B demand for magnets used in different application groups was calculated, based on the key assumptions set out in 4.3.3. According to the scenario results, the overall demand for Nd-Fe-B could increase by factor 3 (low Nd-Fe-B demand scenario) to 6 (high Nd-Fe-B demand scenario) from current (2015) levels to 2030, from around 80-112 kt in 2015 to 240-633kt in 2030 for the low and high Nd-Fe-B demand scenario, respectively (Figure 3; Table 3). Motors for use in small automotive and industrial applications remain the most important group in terms of absolute Nd-Fe-B volumes. The demand for Nd-Fe-B in wind generators is expected to increase until 2030, both in terms of relative importance and in absolute volumes. Furthermore, the demand for Nd-Fe-B in electric two-wheelers, air conditioners, hybrid and electric vehicles and magnetic separators is expected to grow in absolute terms; Nd-Fe-B use for MRI and HDD is stable or declining, generators stable or slowly increasing, acoustic transducers increasing or slowly decreasing.

REE demand for use in Nd-Fe-B magnets has been derived from the composition of the Nd-Fe-B material and tonnes demanded, with a percentage added to account for REE losses during Nd-Fe-B production. For both the high and the low Nd-Fe-B demand scenario, HREE demand for use in Nd-Fe-B magnets is growing slower than the demand for Nd-Fe-B and contained LREE, and LREE demand for use in Nd-Fe-B grows slightly faster than Nd-Fe-B demand. The level of HREE reduction in the magnets was assumed to be higher in the high Nd-Fe-B demand scenario. As a consequence, the estimates for HREE demand do not differ as much between the two scenarios as the LREE estimates.

According to the scenario assumptions, around 7 to 11 kt of HREE and 86 to 234 kt of LREE will be required for Nd-Fe-B production in 2030. Detailed figures for Nd-Fe-B and derived REE demand can be found in Annex A1.

Table 3: REE demand for Nd-Fe-B production, gross demand, including losses in magnet production, tonnes of rare earth metals (in t REM)

		Demand REE for use in different NdFeB application groups, (gross demand incl. losses in magnet production, t REM)							
		2015		2020		2025		2030	
Application group	Unit	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
Electric Two-wheelers	Nd (t)	1600	3740	1860	5360	2150	7690	2500	11070
	Pr (t)	325	765	380	1090	440	1570	510	2260
	Dy (t)	265	445	250	485	225	485	190	410
	Tb (t)	22	37	21	41	19	41	16	34
Air Conditioners	Nd (t)	525	2960	810	4860	1240	7960	1920	13030
	Pr (t)	105	605	165	990	255	1620	390	2660
	Dy (t)	86	290	110	370	130	450	145	485
	Tb (t)	7	24	9	31	11	38	12	40
Traction motors (H)EV	Nd (t)	890	1070	1290	3150	1680	8250	2190	22420
	Pr (t)	180	220	265	645	345	1680	445	4570
	Dy (t)	405	485	345	675	405	1260	470	2180
	Tb (t)	34	41	29	56	34	105	39	185
MRI Scanners	Nd (t)	230	460	150	415	100	375	66	340
	Pr (t)	47	94	31	85	20	77	13	69
	Dy (t)	6	12	4	11	3	10	2	9
	Tb (t)	0	1	0	1	0	1	0	1
Wind Generators	Nd (t)	1490	3250	2110	4600	4090	22000	7910	44410
	Pr (t)	305	665	430	940	835	4490	1610	9060
	Dy (t)	180	385	220	415	370	1390	605	1640
	Tb (t)	15	32	18	35	31	115	51	140
HDD	Nd (t)	1020	1220	950	1310	810	1400	705	1520
	Pr (t)	210	250	195	265	165	285	145	310
	Dy (t)	0	0	0	0	0	0	0	0
	Tb (t)	0	0	0	0	0	0	0	0
Acoustic Transducers	Nd (t)	2030	2030	1840	2360	1660	2730	1500	3170
	Pr (t)	415	415	375	480	340	560	305	645
	Dy (t)	0	0	0	0	0	0	0	0
	Tb (t)	0	0	0	0	0	0	0	0
Magnetic Separators	Nd (t)	970	970	1030	1200	1090	1490	1160	1850
	Pr (t)	200	200	210	245	220	305	235	380
	Dy (t)	105	105	100	100	95	90	89	69
	Tb (t)	9	9	9	9	8	8	7	6
Other Generators	Nd (t)	235	240	240	295	245	355	255	425
	Pr (t)	48	49	49	60	51	72	52	87
	Dy (t)	84	79	79	78	73	75	67	70
	Tb (t)	7	7	7	7	6	6	6	6
Other Motors	Nd (t)	7070	8130	11520	14670	18770	26450	30580	47680
	Pr (t)	1440	1660	2350	2990	3830	5400	6240	9730
	Dy (t)	840	970	1200	1330	1700	1670	2340	1770
	Tb (t)	71	81	100	110	140	140	195	150
Other NdFeB applications	Nd (t)	6740	8160	10090	14790	15110	26780	22600	48440
	Pr (t)	1380	1670	2060	3020	3080	5460	4610	9890
	Dy (t)	1270	1440	1660	2090	2140	2900	2690	3710
	Tb (t)	105	120	140	175	180	245	225	310
Sum	**Nd (t)**	**22810**	**32240**	**31890**	**53010**	**46950**	**105480**	**71370**	**194360**
	Pr (t)	**4650**	**6580**	**6510**	**10820**	**9580**	**21530**	**14570**	**39660**
	Dy (t)	**3240**	**4210**	**3970**	**5560**	**5130**	**8330**	**6600**	**10350**
	Tb (t)	**270**	**355**	**335**	**465**	**430**	**700**	**555**	**865**

Table 4: Supply of Nd-Fe-B material from EOL magnets in years 2015-2030 (t Nd-Fe-B available for recycling, excluding material losses from collection and disassembly)

	Supply NdFeB from EOL appliances from different NdFeB application groups (t NdFeB available for recycling, excluding material losses from collection and disassembly)							
	2015		2020		2025		2030	
Application Group	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
Electric Two-Wheelers	2820	5660	4090	9250	4670	13010	5270	18240
Air Conditioners	490	865	655	1880	890	4320	1330	7480
Traction Motors (H)EV	2	3	70	84	735	955	2480	4310
MRI Scanners	455	540	585	1070	635	1290	425	1020
Wind Generators	8	8	78	85	440	555	1480	2390
Hard disk drives	1330	1480	1520	1730	1240	1550	1030	1550
Acoustic Transducers	1470	1910	1470	1530	1510	1680	1370	1950
Magnetic Separators	1730	1730	1990	1990	2110	2180	2220	2590
Other Generators	32	37	210	235	610	665	905	955
Other Motors	1010	1010	3880	3930	6380	6950	9910	12020
Other NdFeB applications	410	410	525	550	750	920	1100	1620
Sum	**9750**	**13650**	**15070**	**22340**	**19970**	**34070**	**27530**	**54120**

4.4.2 The potential for secondary rare earth supply from EOL magnets, global scope, low and high Nd-Fe-B demand scenario, and derived REE supply

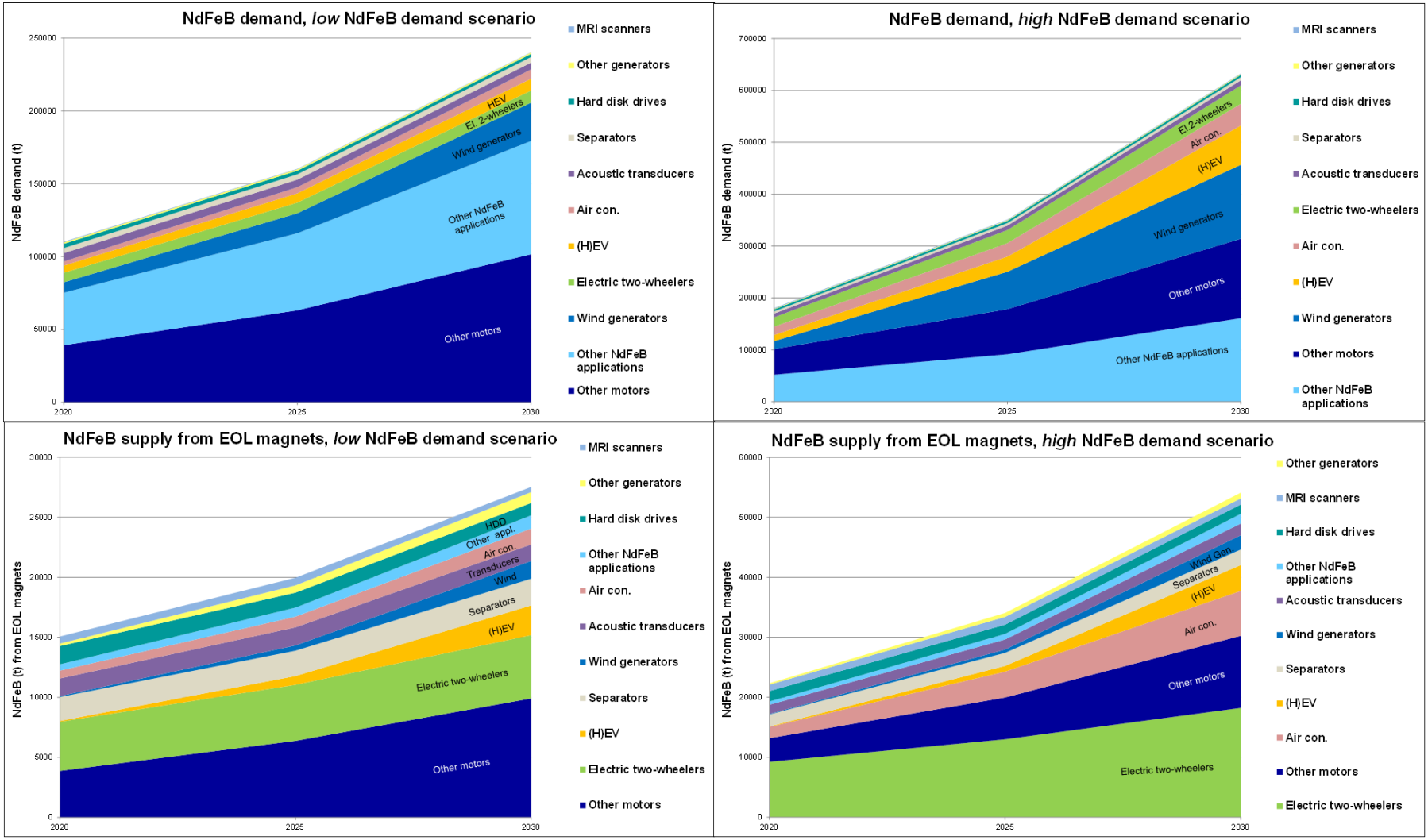

Figure 3: Nd-Fe-B demand and net Nd-Fe-B supply from EOL magnets (expected Nd-Fe-B material from appliances reaching EOL; losses during collection & disassembly have been subtracted), low and high Nd-Fe-B demand scenario, years 2020-30, tonnes Nd-Fe-B

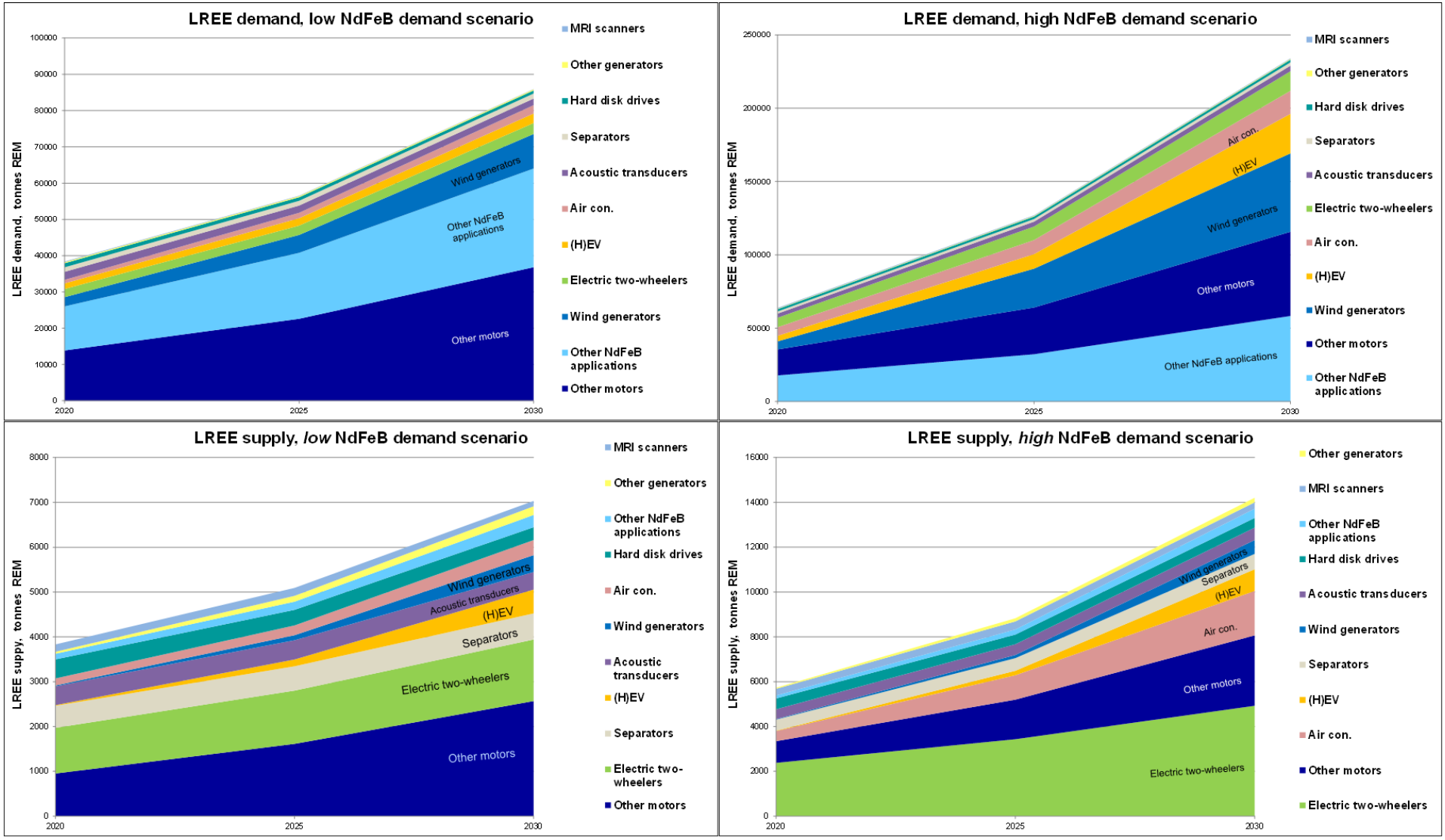

Figure 4: LREE demand for use in Nd-Fe-B magnets (gross demand of Nd and Pr (Di,j), including expected losses during magnet production), and potential LREE supply from recycled EOL magnets (Snet,i,j), with losses during collection, disassembly and recycling subtracted, low and high Nd-Fe-B demand scenario, years 2020-30, in tonnes REM (sum Pr and Nd)

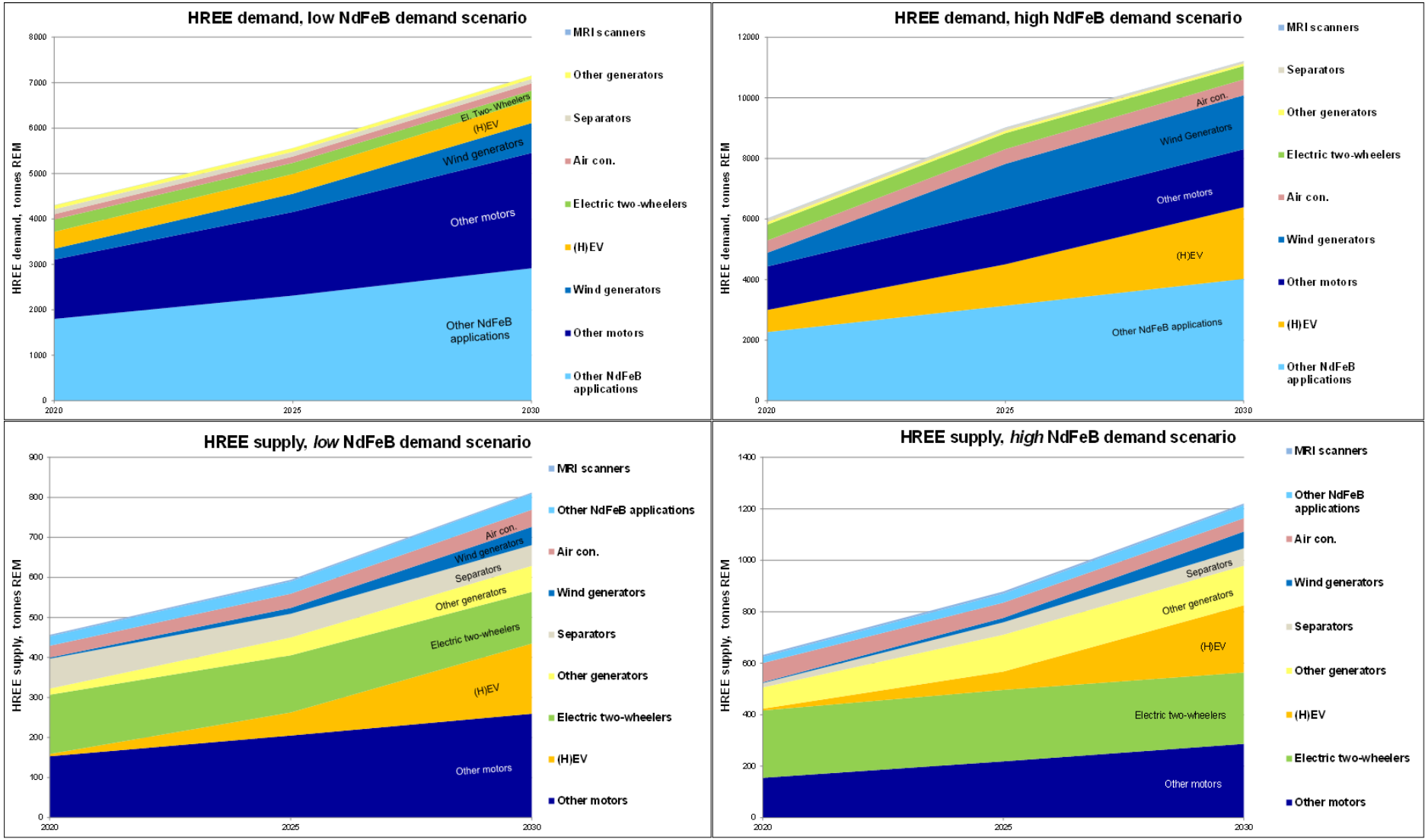

Figure 5: HREE demand for use in Nd-Fe-B magnets (gross demand of Dy and Tb (Di,j),, including expected losses during magnet production), and potential HREE supply from recycled EOL magnets (Snet,i,j), with losses during collection, disassembly and recycling subtracted, low and high Nd-Fe-B demand scenario, years 2020-30, in tonnes REM (sum Dy and Tb)

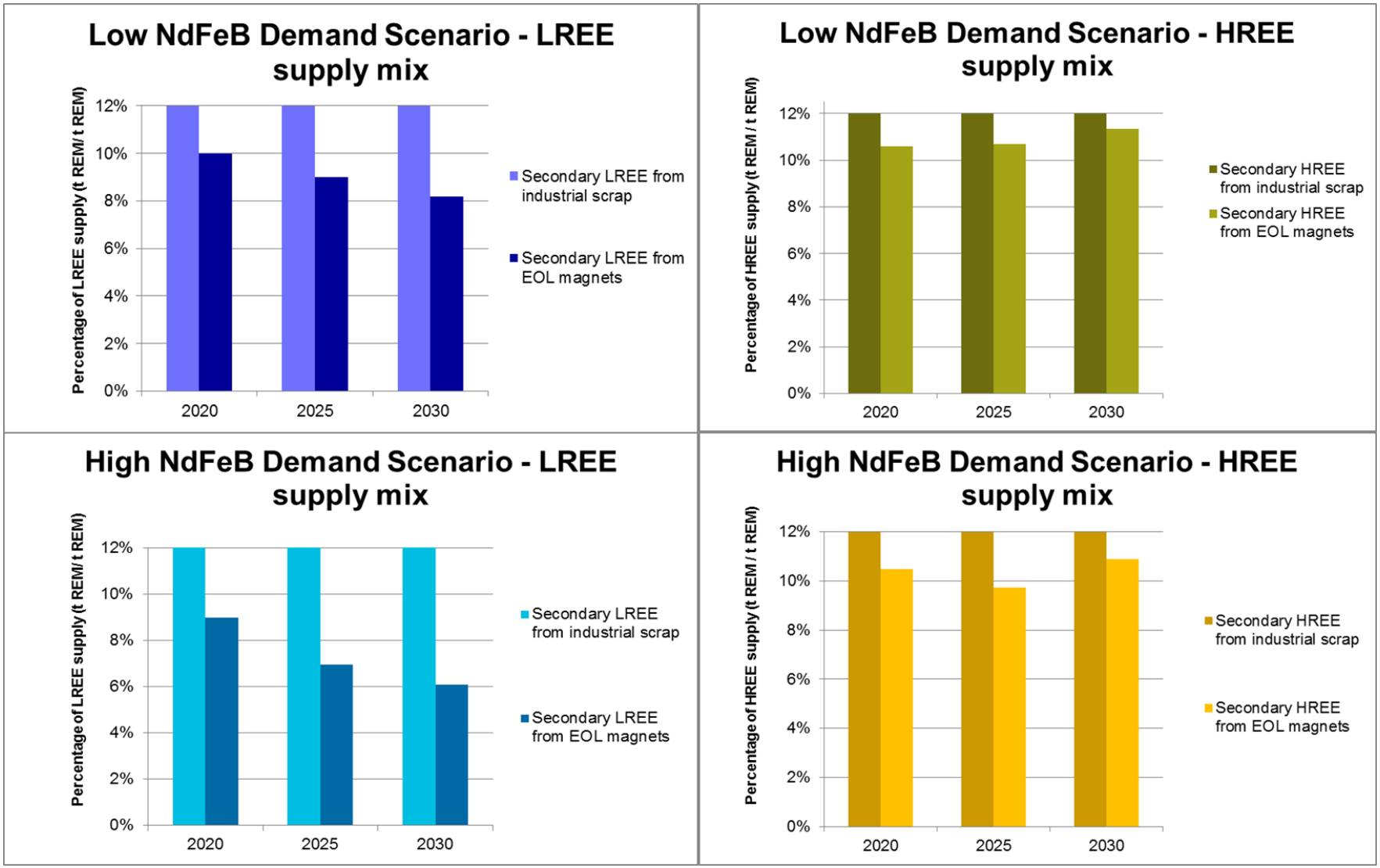

Figure 6: Potential RIR (Recycling input rate, percentage of LREE (HREE) supply for use in Nd-Fe-B production which can be met from secondary sources, low and high NdFeB demand scenario (% of REM supply)

The estimated net availability of secondary Nd-Fe-B supply from EOL magnets in years 2020-2030 is shown in Figure 3. The underlying data can be found in the Annex A1. Material losses expected to occur from the collection and disassembly stages have been deducted from the gross supply figures of magnets from EOL appliances. Net potentials for secondary HREE and LREE production were then calculated, based on the average composition of the net EOL Nd-Fe-B material arising in the respective year (Figure 4, Figure 5). REE losses expected during the recycling process have been deducted.

Currently, (2015 estimates) electric two-wheelers, acoustic transducers, magnetic separators, HDD and “other motors” (see Figure 3) constitute interesting sources of Nd-Fe-B material from EOL appliances in terms of the quantities of secondary material expected to become available as input materials for a secondary rare earth production route. The percentage contribution of magnets from “other motors” roughly doubles in both scenarios between 2015 and 2020. Air conditioners could constitute an important source, but with larger differences between the two scenarios. By 2030, “other motors”, traction motors from hybrid and electric vehicles and electric two-wheelers are likely to dominate as potential sources for EOL Nd-Fe-B magnets, in different orders of importance for the low and the high Nd-Fe-B demand scenario. Compressor motors from air conditioners and separators constitute other potentially interesting sources of EOL magnets.

The supply for LREE from EOL magnets follows a similar trend to that of Nd-Fe-B material in general. For HREE, electric two-wheelers, separators, other motors and air conditioners are important sources of EOL magnets in the near future. By 2030, (H)EVs, electric two-wheelers and other motors are most significant. The supply quantities are subject to HREE content reduction assumptions made for the demand scenarios.

4.4.3 Potential quantities of from pre-consumer magnet scrap to become available for secondary REE production

The potential supply of pre-consumer scrap available for indirect recycling routes was derived from the global Nd-Fe-B production figures, assuming that 20% of starting alloy for magnet production becomes scrap destined for the indirect recycling route (same assumption as in section 4.3.3), (Table 5). The clean processing waste suitable for direct recycling is not included in these estimates; it was assumed that this fraction is processed in a direct internal recycling route. Indirect recycling of processing scrap is already being practiced, but details on the recycling processes are not available.

Table 5: Industrial processing waste not suitable for direct (material) recycling route

Scrap estimates - wet scrap suitable for indirect recycling routes			
	2020	2025	2030
t Nd-Fe-B - low demand scenario	28	40	60
t Nd-Fe-B - high demand scenario	45	88	158

4.4.4 Overall potential of secondary REE to meet REE demand for Nd-Fe-B

Estimates are provided for the percentages of the LREE and HREE supply mixes for use in Nd-Fe-B production which can be met by secondary sources in years 2020, 2025 and 2030, according to scenario assumptions made in this study (Figure 6). The modelled scenarios show that 18-22% of global light (Nd and Pr) and 20-23% of heavy (Dy and Tb) REE demand for use in Nd-Fe-B magnet production can be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30 (range of RIR values for individual years and scenarios). Results show a decline

in the relative contribution of secondary REE to the potential LREE supply mix, and a small increase for HREE.

The overall decline in the percentage LREE supply from secondary sources is due to the declining relative contribution from EOL magnets. It shows that according to the scenario estimates, the demand for LREE used in Nd-Fe-B magnets grows faster than the LREE supply from EOL magnets. For LREE, the rate of the decline differs between the low and the high Nd-Fe-B scenario. For HREE, there are only small differences between the low and the high Nd-Fe-B demand scenarios in this percentage contribution trend, due to the mitigating effect of faster HREE reduction assumed for the high Nd-Fe-B demand scenario.

According to the estimates, the supply potential for LREE from EOL magnets is lower than the potential of LREE from wet processing scrap. The gap widens due to the assumed high annual growth rates of LREE for use in Nd-Fe-B magnets. The supply potential for HREE from EOL magnets is of similar magnitude as the potential from the processing waste in years 2020-30, as a result of the HREE content reduction efforts.

4.5 Discussion and conclusions regarding the potential for secondary REE production from Nd-Fe-B scrap

The modelled scenarios show that between 18-22 percent of global light (Nd and Pr) and 20-23 percent of heavy (Dy and Tb) REE demand for use in Nd-Fe-B magnet production can be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30 (range of RIR values for individual years and scenarios), a significant potential from a resource conservation and environmental impact point of view. The fraction of HREE demand which can be met by secondary sources is increasing over time in both scenarios. The results also indicate that the importance of different EOL Nd-Fe-B applications changes over the time period considered, resulting in a changing mix of components to be handled by disassemblers, and a variability of the magnet material input to be handled in Nd-Fe-B recycling processes. Estimates for absolute volumes of HREE available for recycling are lower if the ongoing HREE reduction efforts were considered in the quantification of secondary REE supply, with a time delay in the order of magnitude of the weighted average product lifetime. Lower demand growth rates for HREE also mean that a larger percentage of the HREE demand can come from secondary sources over time. Substitution and recycling both are strategies to mitigate rare earth criticality. However, substitution and recycling are also competing strategies, since the alleviated supply shortage achieved by reduction or substitution can make recycling less economically viable, and vice versa. Despite that, it has been suggested that recycling and dysprosium reduction make good complementing strategies to avoid dysprosium supply shortages (Seo and Morimoto, 2014). Substitution and REE reduction efforts could help stabilize the market for REE used in Nd-Fe-B magnets, which would facilitate planning for Nd-Fe-B recyclers.

The “European Rare Earths Competency Network“ (ERECON) put together a list of priority products for which Nd-Fe-B recycling is most likely to become economically viable – see ERECON (2015). The list includes HDD, automotive applications, motors in industrial applications, acoustic transducers, air conditioners, mixed electronics, electric bikes and wind turbines. The results from this study indicate that electric two-wheelers and magnetic separators could play a bigger role than the ERECON report suggests[15]. However, this difference can be explained by the difference in geographical scope –the ERECON network focusses on Europe; this study provides global estimates. At least for electric two-wheelers, this observation is not surprising, since the majority of EOL products arise outside Europe.

[15] This is based on global EOL magnet recycling potentials quantified in this study for 2015 and 2020.

Scenario estimates of future Nd-Fe-B demand are inherently uncertain, but the uncertainties are further enhanced by the speed of market developments at both magnet material and component levels (motors, generators) and the diversity of applications. Uncertainties associated with data quality issues regarding REE content in EOL applications/ magnets have previously been highlighted (Chancerel et al., 2015; Guyonnet et al., 2015). Losses during collection, disassembly and recycling were assumed for each application group, but were kept constant during the time period considered for simplification. In reality, the overall material recovery rates are currently low, but could increase over time as collection and recycling schemes are being established.

The global focus of this study meant that issues related to the practical implementation of recycling, such as the level of (de-)centralization required for Nd-Fe-B recycling of global scrap quantities, were not addressed. A local quantification of potential secondary REE supply from Nd-Fe-B recycling would be suited to address the potential of recycling to alleviate the supply risks of individual REEs, which are not a uniform global issue. It has been suggested that the recycling of EOL Nd-Fe-B magnet material arising in Europe could meet the demand of the local magnet producers (ERECON, 2015). The results of this study can serve as a reference and starting point for more detailed investigations, if particular application groups or the secondary REE potentials obtainable in a specific country or region are investigated.

The quantification of secondary REE supply was undertaken against the background of environmental impacts associated with REE production, and supply risks outside China, yet with a global perspective. Since most Nd-Fe-B magnet production happens in China, it would be interesting and relevant to see if substitution, rare- earth magnet free technology alternatives and REE recycling efforts driven by policy makers and industry outside China will find followers within China, if for reasons other than supply risk alleviation. This would help improve global HREE demand projections. Furthermore, the Chinese market drives demand for many Nd-Fe-B applications (electric two-wheelers, rare-earth compressor motors for air conditioners, wind turbines…), so both EOL magnets and production scrap are likely to arise in China in large quantities. From a European perspective, it would therefore be interesting to investigate potential collaborations with China when setting up recycling schemes. Recycling collaborations with China should therefore be investigated when following a sustainable resource strategy for REEs with maximized global impact.

Due to time limitations, the scenario assumptions regarding recycling potentials made for this study could not be supported by a detailed analysis of current and future economic barriers to REE production from Nd-Fe-B scrap. (The global scope of the study would have made a life cycle costing exercise more challenging, due to e.g. regional differences in wages in addition to the uncertainties associated with the future outlook of the study). The assumptions in Table 2 should therefore be interpreted as informed estimates made after a thorough review of and reflection on existing studies, from which relevant information was taken into account to improve estimates wherever possible. Furthermore, existing collection schemes for EOL appliances, magnet sizes and composition in relation to the disassembly /extraction effort, and other factors relevant to the likelihood of the EOL appliance use as viable secondary REE feedstock, were taken into account in the estimates. At the time of writing, rare earth prices and economic incentives to introduce recycling schemes for Nd-Fe-B magnets were low, and it was suggested that incentives need to be created if the Nd-Fe-B material available for secondary REE production is to be utilized. Labour costs pose a challenge, at least in high-income countries – see also Habib et al., (2015). In Germany, hard disk drives are sometimes disassembled in prisons to circumvent high labour costs (Brück, 2017; Elwert, 2017b) Economic incentives for recycling have been recommended to attain economic viability of REE recycling processes (see e.g. Chancerel et al. (2015)), and government subsidies have been used to kick-start REE recycling from Nd-Fe-B magnets in Japan. Alternatively, critical metal recycling could be incentivised by regulatory policy. Currently, policies for handling of electronic waste and end-of-life vehicles focus on recycling targets by mass and do not

provide specific incentives for the extraction of magnet material containing critical metals such as REEs, which only make up a small fraction of the product weight. Competition between recyclers of individual material streams has been raised as an issue for EOL Nd-Fe-B collection, with implications for quantities available for recycling, and should be investigated further.

To complement the initially low quantities of EOL magnets, the use of industrial scrap as a feedstock to the same process has been suggested (Bast et al., 2015). The findings from this study support this view: Global supply of secondary Nd-Fe-B material from pre-consumer sources is likely to exceed the potential supply from EOL magnets in the time period considered. Its utilization could help recyclers reduce the risk of not obtaining enough input material for recycling. The scenario results illustrate a dynamic market, a large variety of Nd-Fe-B containing products reaching EOL, and a changing composition of Nd-Fe-B manufacturing scrap and EOL magnets, expected due to different demand growth rates of different magnet application groups, and changes to the engineering of the magnet materials. This suggests that a focus on recycling processes which are capable of handling changing input compositions could be a beneficial future strategy.

Despite economic challenges, the extraction of REE from Nd-Fe-B magnets offers some benefits. REE recycling is beneficial over primary REE production from an environmental and resource conservation perspective (Schüler et al., 2011; Sprecher et al., 2014b; Walachowicz et al., 2014). Recycling as a supply risk mitigation strategy is associated with lower investment cost than the establishment of new mines, and the decentralized “urban mine” offers some flexibility compared with the current primary supply, which is largely from one country. Despite the challenges associated with the compositional variation of the magnets, the REE composition of the EOL magnets/ industrial processing scrap is closer to the desired REE ratio required in the production of new magnets than the ores, which allows for more efficient, shorter processing.

Chapter 5 - Filling LCA data gaps: REE production from ion-adsorption clay deposits

To answer the overall research question, a dataset had to be created for the assessment of primary rare earth production from ion- adsorption deposits, since the datasets available in the literature are not representative of the main production route for heavy rare earths, such as dysprosium and terbium. Therefore, this necessary background information was compiled, and is presented in this chapter. The chapter starts with a process description for the mining of rare earths from this route, and the following separation steps, followed by a description of environmental impacts discussed in the literature. Then, the life cycle inventory and impact assessment results are presented, and limitations associated with the assessment discussed.

5.1 Introduction

As described in the previous two chapters, the demand for Nd-Fe-B magnets has grown, one of the reasons being efficiency gains in motor applications (Buchert et al., 2013; Waide and Brunner, 2011). The growth in demand for Nd-Fe-B magnet material used in motors has led to an increase in demand for heavy rare earths (HRE), especially dysprosium.

The recent demand increase has sparked a growing interest in the assessment of environmental impacts associated with rare earth production. A life cycle inventory of light rare earth production, based on the process route from bastnaesite conducted at the main production site in Bayan Obo (LREE-rich mineral deposits), has been implemented in the ecoinvent database for some time (Althaus et al., 2007). Further life cycle assessment studies have been published in recent years (Browning et al., 2016; Graf, 2012; Koltun and Tharumarajah, 2014; Sprecher et al., 2014b; Zaimes et al., 2015). However, the process routes addressed by the above mentioned studies are not representative of the main production route for heavy rare earths: Most heavy rare earths are mined from ion-adsorption clay deposits in Southern China (Talens Peiró and Villalba Méndez, 2013); and in-situ leaching is now the legally required production method for REE from these deposits (Yang et al., 2013).

First, a detailed process description of REE production from ion-adsorption clay deposits through in-situ leaching and solvent extraction is presented (Section 5.3) and environmental impacts linked with the process reported (Section 5.4). A life cycle inventory to represent this process is then compiled (Section 5.5). Vahidi et al. (2016) have compiled a dataset for in-situ leaching from ion-adsorption clay deposits. Their study, based on information from Chinese literature, covers the production of a rare earth concentrate from the in-situ leaching process. Here, the system boundaries are extended to include another key downstream processing step into the dataset; the separation of RE concentrates into individual REEs through solvent extraction. In section 5.7, the technical difficulties of REE production from decreasing ore grades which constitute a topic for research in China are presented, and recommendations for further research required to further improve the dataset are given. Finally, shortcomings of common life cycle impact assessment (LCIA) methodology to address the environmental impacts associated with rare earth production through this route are highlighted.

5.2 Methods

A life cycle inventory dataset for rare earth production from ion-adsorption clays was compiled, with the aim to provide this data for use in further life cycle assessment studies. This was done according to the current ISO 14040 / 14044 standards (DIN EN ISO, 2006a, 2006b). All stages of the life cycle assessment were conducted in order to be able to analyze the dataset and compare it against impact as-

sessment results for other rare earth production routes. The modelling was done with the OpenLCA software (V.1.5) and with background datasets from ecoinvent 3.2.

Prior to the data compilation, a review of both peer-reviewed and grey literature was conducted to obtain both qualitative and quantitative information on the current practice of rare earth production (mining and processing) from ion-adsorption clay deposits. A literature search was also conducted to obtain information on reported environmental impacts associated with rare earth production to assist the interpretation of the datasets compiled for this study, and to check whether the life cycle inventory adequately reflected the issues. The information found in the literature was complemented by interviews with industry experts.

5.3 Production of individual rare earth oxides from ion-adsorption clay deposits via in-situ leaching and solvent extraction

5.3.1 Characterization of deposits

Most HREE are mined from ion-adsorption clay deposits in Southern China (Talens Peiró and Villalba Méndez, 2013). RE^{3+} ions contained in weathered rocks (sands) of magmatic origin are mobilized under tropical conditions and absorbed to aluminosilicates (Gupta and Krishnamurthy, 2005; Papangelakis, 2014; Voßenkaul et al., 2015). A smaller percentage of rare earths, 5-25% of total rare earth content, is contained in the mineral phase and colloid sediment, but this fraction is not accessible with current mining practice (Krishnamurthy and Gupta, 2016; Tian et al., 2013). The ores occur close to the surface and are characterized by low thorium/ uranium contents. The ore is low-grade, generally only 0.05% to 0.5% REO, with higher heavy rare earth content (Gupta and Krishnamurthy, 2005). Mining is viable only above a certain concentration, with ion-adsorption clay deposits currently mined between 0.2 and 0.4% (Ding, pers. comm.) The deposits are sediments with higher variability between deposits than other ore type, due to the weathering – see (Gupta and Krishnamurthy, 2005; Talens Peiró and Villalba Méndez, 2013; Voßenkaul et al., 2015). The ion-adsorption clay deposits can be broadly classified into two ore types, light and heavy ion-adsorption clay deposits (Voßenkaul et al., 2015), but variations in between (with both significant light and heavy fractions) can also be found. Low cerium contents are characteristic for these deposits, and can be explained by the formation process (Haschke, 2016). Ion-adsorption deposit mining started in Longnan province, where pond leaching was the technique applied. The deposits in Longnan with high yttrium contents (65% of rare earth content) are no longer operational (Ding, pers. comm.). Areas with current or recent operational mines include Ganzhou and Xinfang where deposits with 20 or 30 % of yttrium are mined (Ding, pers. comm.). A composition representative of ores currently mined is shown in Table 6 (Packey, 2016a). The composition represents an official Chinese estimate (Packey, 2016b). Due to the variation of the deposits, the average composition of deposits mined could shift in future.

Table 6: REE contents of ion-adsorption clays, representative of the major producing mines, adopted from (Packey, 2016a), scaled to 100%

REO	Average weight percentage (%)
La_2O_3	27.9
CeO_2	3.3
$Pr_{11}O_6$	5.7
Nd_2O_3	17.8
Sm_2O_3	4.6
Eu_2O_3	0.9
Gd_2O_3	6.0
Tb_4O_7	0.7
Dy_2O_3	3.8
Er_2O_3	2.5
Ho_2O_3, Tm_2O_3, Yb_2O_3, Lu_2O_3	2.4
Y_2O_3	24.5
Sum	**100**

5.3.2 REO concentrate production process from ion-adsorption clays – in-situ leaching

Whilst heap leaching used to be common, in-situ leaching is now the mandatory production route for rare earth mining from ion-adsorption clay deposits in 2011 in China (Yang et al., 2013). Heap leaching has been banned due to environmental concerns. Flow sheets on in-situ leaching of ion-adsorption clays and the following solvent extraction process are available from the literature (Krishnamurthy and Gupta, 2016; Navarro and Zhao, 2014; Vahidi et al., 2016). The leachate is directly inserted into the ore to extract the rare earths in an ion-exchange reaction, and then processed on site to re-extract the rare earths. The mines operate for 1-5 years (Ding, pers. comm.).

Site preparation

The site preparation involves the drilling of holes into the ore body required to insert the leachate and the excavation of precipitation ponds. Equipment needs to be installed for the circulation of the leachate, extraction of the rare earths from the leachate and the removal of impurities, and the heating of the extracted rare earth material to obtain oxides.

Leaching

The leaching solution (with 1-5% ammonium sulfate) is pumped into holes drilled into the ore body, remains in the ground for 150-400 days and is then re-extracted at the bottom, followed by washing of the ore with water (Navarro and Zhao, 2014; Vahidi et al., 2016). However, since the ion exchange kinetics are fast (Papangelakis, 2014), the time span can be much shorter and washing may not always be practiced (Ding, pers. comm.).

Ion exchange with ammonium sulfate:

$$2\ (clay)REE + 6\ NH_4^+ + 3\ SO_4^{2-} \rightarrow 2\ (clay)(NH_4)_3 + REE_2^{3+} + 3\ SO_4^{2-} \qquad \text{[Equation 1]}$$

(Equation 1 based on Vahidi et al. (2016))

Approximately 8-20% of the leachate is lost in the ore (Ding, 2016; Vahidi et al., 2016), possibly due to the heterogeneity of the mined layer in the ore body. In addition to this loss, the NH_4^+ ions which are exchanged against the rare earth ions stay in the ore, i.e. they are emitted to soil. Cations other than REEs (Al^{3+} ,Ca^{2+} ,Mg^{2+} and Fe^{3+}) are also unintentionally extracted in the process, i.e. NH_4^+ ions additional to those required to exchange the accessible rare earth content are exchanged (Chi et al., 2003; Jun, 2011; Yanfei et al., 2016). Sulfate anions from the leachate are also emitted to soil.

Typical compositions of the leaching solution contain 1-8g/l of RE_2O_3 and impurities – see Table 7 (Chi et al., 2003). The percentage of impurities contained in the leachate generally increases with decreasing ore grades.

Removal of impurities in leachate (through selective precipitation)

After extraction from the ore, the pregnant leachate is moved to one of the ponds to undergo precipitation to remove impurities. Aluminum ions in particular cause a technical challenge since they disturb the REE precipitation process by causing flocculation (formation of agglomerated rather than crystalline particles), and are therefore removed at pH 5, before rare earth precipitation (Luo et al., 2015). Fe^{3+} and Mg^{2+} ions precipitate under very similar conditions and can therefore be removed in the same process (Chi et al., 2003). Ammonium bicarbonate is added to the leachate for two reasons: to achieve the required conditions for precipitation by increasing the pH of the leachate from ~3.5 to ~5, and as the precipitating agent (providing the OH^- ions from the reaction of bicarbonate ions with water) (Chi et al., 2003).

The removal rate for aluminum ions depends on the pH of the solution, but also on the concentrations of Al^{3+}, other impurities and RE in the leachate (Chi et al., 2003; Luo et al., 2015). Around 95% of Al ions and 5% of RE ions are typically extracted (Luo et al., 2015). Problems occur particularly in leachates with low rare earth contents (< 2 g/l) where the Al ion content is high relative to the RE content: only ~70% of Al are precipitated and ~25% of RE content is lost (Luo et al., 2015). As a consequence, the process is less efficient and consumes more ammonium bicarbonate for lower ore grades, and also gets less efficient throughout the operation of the mine, since the leachate is recirculated and rare earth content in the leachate decreases during the operation. Equations 2 and 3 from Chi et al. (2003) show the intended precipitation reaction (2) and the unintended side reaction (3).

$$Al^{3+} + 3\ HCO_3^- \rightarrow Al(OH)_3\downarrow + 3\ CO_2\uparrow \qquad \text{[Equation 2]}$$

$$REE^{3+} + 3\ HCO_3^- \rightarrow RE(OH)_3\downarrow + 3\ CO_2\uparrow \qquad \text{[Equation 3]}$$

The aluminum hydroxide impurities are filtered off after the precipitation to remove them from the leachate. The impurities which cannot be extracted in this process (mainly Ca^{2+} ions) end up in the REE concentrate after heating, which contains around 7% of impurities by mass, and are then removed during SX (solvent extraction) (Jun, 2011).

Extraction of REE from leachate through precipitation and heating

After filtering off the metal hydroxides, the REE and remaining Ca^{2+} impurities are extracted through another precipitation process. Both ammonium bicarbonate and oxalic acid can be used as precipitants (Vahidi et al., 2016). However, ammonium bicarbonate is cheaper and much more common for the precipitation of rare earths before separation (Chi et al., 2003; Lartigue-Peyrou, 2016; Vahidi et al., 2016). (Oxalic acid is commonly used for rare earth precipitation after separation (Lartigue-Peyrou, 2016)).

Precipitation with ammonium bicarbonate (from Chi et al. (2003))

$2\ REE^{3+} + 3\ HCO_3^- \rightarrow RE_2(CO_3)_3 + 3\ H^+$ [Equation 4]

Carbonic acid decomposition (from Chi et al. (2003))

$H^+ + HCO_3^- \rightarrow H_2O + CO_2$ [Equation 5]

Heating of rare earth carbonates to obtain oxides (from Lin et al. (2015))

$RE_2(CO_3)_3 \rightarrow$ (heating) $RE_2O_3 + 3\ CO_2$ [Equation 6]

Rare earths are precipitated from the leachate as carbonates. The efficiency of the reaction is pH dependent: The pH determines the fraction of ammonium bicarbonate present as carbonate ions, and therefore the overall amount of reagent needed to precipitate all REE ions as carbonates (Chi et al., 2003). The required pH is achieved through further addition of ammonium bicarbonate (which here again acts as precipitant and pH regulator). Furthermore, ammonium bicarbonate is consumed for carbonic acid decomposition [Equ. 5] (without which the solution would gradually get more acidic (Chi et al., 2003) see [Equ. 4]). The extraction rate for rare earths in this step is around 95% in this step (around 5% of REE content is lost in each precipitation step), according to lab experiments (Chi et al., 2003).

Usually, two or three precipitation ponds are placed next to each other to manage overflow (Ding, pers. comm.). Agitation is achieved by the continuous pumping of the REE containing leachate from the ore and the leachate is recirculated back into the ore until the rare earth content in the leachate is so low that further processing is no longer viable (Ding, pers.comm). The purity of the RE after precipitation is around 91-93% (Schüler et al., 2011; Vahidi et al., 2016). RE carbonates are then heated to 800-900°C to convert them to mixed rare earth oxides (Chi et al., 2003), [Equ. 6]. After a leaching step, they are then separated in a multi-stage SX process in a centralized location.

Management of leachate / waste water treatment

During the mining operation, the leachate is pumped into the ore body. Part of the leachate is lost in this process, i.e. cannot be re-extracted.

In the leaching process, NH_4^+ ions from the leachate are transferred to the ore body and RE ions and impurities are taken up into the leachate. First impurities and then rare earths are precipitated in nearby ponds; the leachate composition is adjusted (pH, ammonium bicarbonate content) and pumped through the ore body again. This process is stopped when the RE content gets so low that further processing of the leachate is no longer viable. Once the operation ceases, leachate is collected and can be reused at another mining site (Ding, pers. comm.). Ponds are refilled with the excavated material and planted with vegetation.

During the operation, almost all of the leachate is recirculated, and waste water leaving the system is not usually generated (Ding, pers. comm.). This is possible because of the constant removal of the metal impurities throughout the operation. When the operation finishes, the reuse of the leachate at other mining sites is possible, in which case the generation of waste water can be avoided or minimized. However, high concentrations of ammonium in the discharge water far exceeding standards are also mentioned in the literature (Krishnamurthy and Gupta, 2016). Hence, the reuse of the leachate at other sites may not always be practiced, e.g. in the case of illegal mining. It can be seen in Figure 7 that the potential reuse of leachate after the mining operation finishes has a big influence on the net $(NH_4)_2SO_4$ consumption.

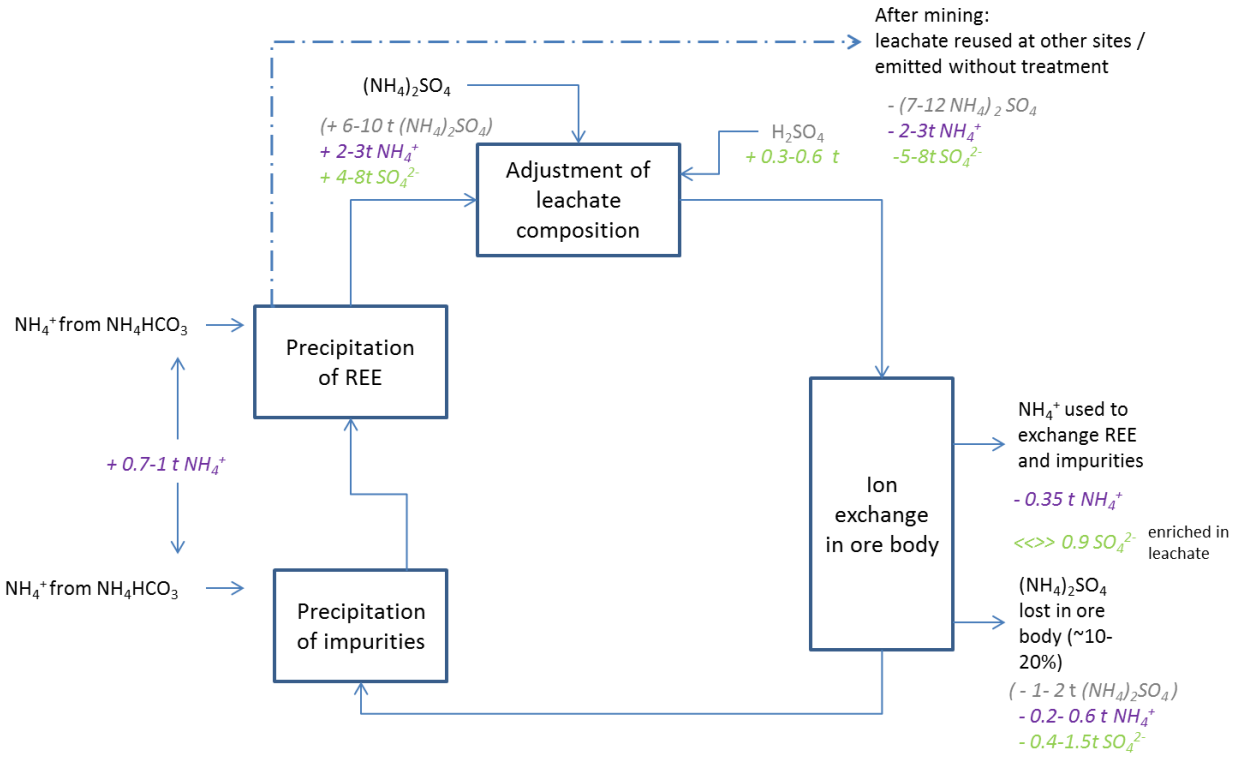

Figure 7: Illustration of leachate balance (t per t unseparated REO concentrate, 91% purity, from ion-adsorption clays)

Recovery rates and decreasing ore grades

Some literature sources report high rare earth recovery rates for REE mining from ion-adsorption clays, (e.g. 85-90% (Papangelakis, 2014), however, these recovery rates can only be achieved with the previously practiced heap-leaching technique (Ding, pers. comm.). For in-situ leaching, only around 40-70% are currently recovered (Ding, pers. comm; Lartigue-Peyrou, pers. comm). Tian et al. (2013) state that RE recovery rates from in-situ mining of ionic deposits are low. Differences in recovery rates are also associated with different ore grades. Illegal mining of ion-adsorption clay deposits is a cause for decreasing ore grades in the ore bodies left to the legal miners. Illegal miners selectively focus on higher-grade deposits, thereby lowering their own production costs and reducing the economic viability of the remaining degraded deposit (Packey, 2016a). Although an effort is made to curb illegal production activities, the illegal fraction of the market is still notable at around 30-40% (Packey, 2016a), which illustrates the importance of the ore degradation issue.

It has been reported that the processing costs per unit of output increase with decreasing ore grades, since larger inputs of chemicals and energy are required (Calvo et al., 2016; Krishnamurthy and Gupta, 2016; Tian et al., 2013). The mining of leaner ores is technologically challenging and associated with lower leachate recovery rates and higher contents of ammonium in discharge water, exceeding environmental standards (Krishnamurthy and Gupta, 2016). The leach selectivity is lower, i.e. larger quantities of elements other than rare earths are involuntarily extracted (Jun, 2013). Due to the higher content in impurities, the processing of pregnant leachates from leaner ores with lower rare earth contents reduces the efficiency of the precipitation process, with increased consumption of precipitants and decreased rare earth recovery rates (Jun, 2013; Tian et al., 2013). The decreased recovery rates are associated with the unintended side reaction during the aluminum removal from the leachate.

The recovery of the rare earth fraction that is not present as exchangeable ions in the clays would require a leachate with pH <3 (Yanfei et al., 2015). However, this would mean that colloidal sediment

phase aluminum would also be liberated, and the amount of aluminum present in this phase far exceeds the amount of rare earths (Yanfei et al., 2015). This would cause issues in the currently practiced precipitation process.

5.3.3 Production of individual rare earth oxides through solvent extraction

Separation of individual rare earths is technically difficult; especially for neighboring elements. Up to hundreds of separation stages may be employed to separate the REE in one feedstock (Xie et al., 2014) Solvent extraction (SX) is commonly used for industrial-scale separation of rare earths (Leveque, 2014; Xie et al., 2014). Figure 8 shows the typical processing route for rare earth concentrates obtained from ion-adsorption clay deposits (Chun-Sheng et al., 2016). The SX process for rare earths from ion-adsorption clay deposits starts by leaching the rare earth concentrates, typically with HCl, sometimes with HNO_3 or H_2SO_4 solutions (Krishnamurthy and Gupta, 2016; Xie et al., 2014), to bring the rare earths into solution. Mixer-settlers are used as the standard equipment for the separation process (Leveque, 2014).

During the operation of the mixer-settlers, i.e. the extraction process, the aqueous and the organic phases are repeatedly contacted (through mixing) and then again left to separate (settling). The movement of the phases is achieved by pumping at least one of the phases (Chalmers, 2015). During contact, the extractant selectively extracts either a group of rare earth elements (at earlier separation stages, when the REE are first separated into groups), or an individual element (during the late separation stages, if/when separation into individual rare earth oxides is intended). H^+ ions which are exchanged for RE during the extraction step (Equ. 7) need to be neutralized (saponified) with NaOH to maintain the pH required for the exchange reactions (Elwert et al., 2013; Gupta and Krishnamurthy, 2005).The extraction raffinate (aqueous phase enriched with some of the REE elements) can directly enter the precipitation stage, during which the REE are precipitated from the raffinate, whereas the loaded solvent, i.e., the organic phase, undergoes an additional ‘cleaning’ step called scrubbing before the target element(s) can be extracted (Elwert et al., 2013). During scrubbing, REE which were unintentionally co-extracted to the organic phase are removed from the organic phase. Then, the target REE can be recovered from the scrubbed organic phase in the so-called stripping step, which is followed by precipitation of REE. The precipitated REE are then washed and calcinated (Chun-Sheng et al., 2016). After scrubbing and stripping, the organic phase is again free from REE and impurities and recirculated, whereas the aqueous phase is neutralized and discharged after recovery of REE through precipitation (Chun-Sheng et al., 2016).

The organic phase (the solvent) consists of an extractant, which chemically reacts with the species to be extracted, and a diluent, which helps to make the phase less viscous (Leveque, 2014).The separation of REE from ion-adsorption clay deposits is typically conducted with P507[16] and naphthenic acid as extractants and kerosene as diluents (Chun-Sheng et al., 2016; Krishnamurthy and Gupta, 2016; Schüler et al., 2011). P507 only features small separation factors for some elements, which is why different systems are currently used in combination to separate the 15 REE from ion-adsorption clays to 3N-5N purity – (see Figure 8, based on Chun-Sheng et al., 2016). For the separation of yttrium, naphthenic acid in kerosene is added to iso-octanol (Chun-Sheng et al., 2016; Krishnamurthy and Gupta, 2016).

SX – general exchange reaction for organophosphorus acids

$$RE^{3+}_{(aq)} + 3\,(HA)_{2(org)} \rightleftharpoons (HA_2)_3RE_{(org)} + 3\,H^+_{(aq)} \qquad \text{[Equation 7]}$$

[16] For REE production in general, D2EHPA is the extractant most commonly used to recover REE from sulfate media (e.g. for REE obtained through the Bayan Obo route, and P507 is the main major solvent for REE elements separation in REE chloride media Ding (2016).

(Equation based on Elwert et al. (2013), Gupta (2005) – HA denotes extraction agent in diluent)

Precipitation with oxalic acid (Vahidi, 2016):

$2\ RE^{3+} + 3\ H_2C_2O_4 + xH_2O \rightarrow RE_2(C_2O_4)_3 \cdot xH_2O + 6\ H^+$ [Equation 8]

Calcination of rare earth oxalates

$2\ RE_2(C_2O_4)_3 + 3\ O_2 \rightarrow$ (heating) $2RE_2O_3 + 12\ CO_2$ [Equation 9]

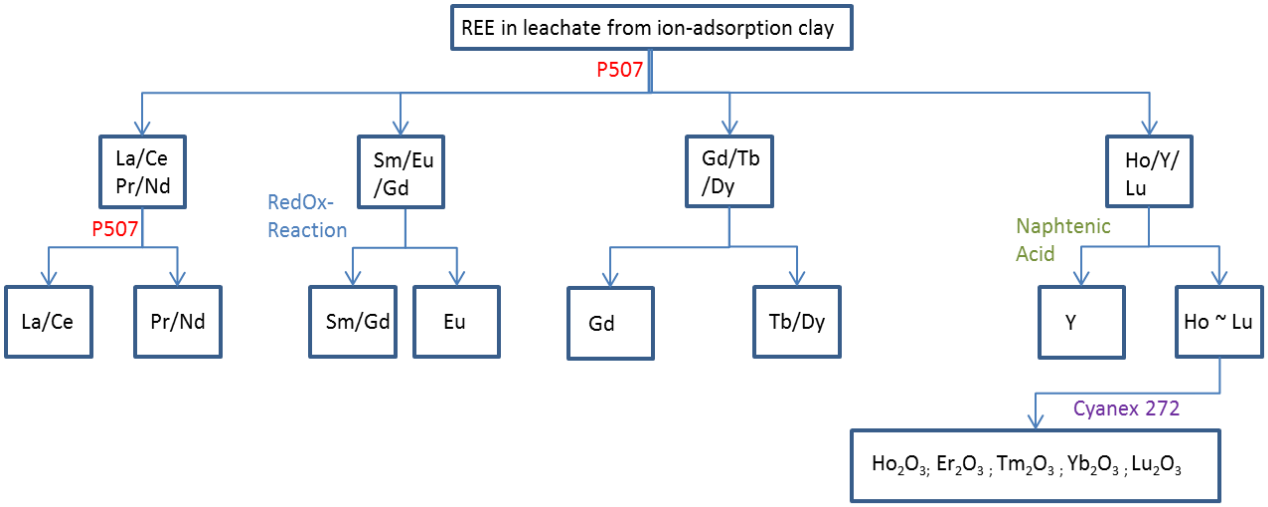

Figure 8: Separation of Rare earth elements from concentrates from ion-adsorption clay deposits - simplified process diagram based on (Chun-Sheng et al., 2016)

5.4 Environmental impacts associated with REO production from ion-adsorption clays reported in the literature

Environmental impacts arise at the mining site and during the separation process. Environmental impacts linked to in-situ leaching of REE are associated with the extraction of rare earth resources, the land use for the mining site itself and the precipitation ponds, emissions to the environment, and upstream impacts associated with the production of the energy used for pumping, heating of carbonates, filtering, and chemical production. It should be noted that ion-adsorption clay deposits are advantageous over other rare earth deposits in terms of their lower radioactivity levels (Packey, 2016a; Voßenkaul et al., 2015). Environmental impacts associated with the separation process are attributable to the energy consumption associated with the operation of the mixer-settler units and calcination furnaces, solvent losses[17], water consumption, and the salt contained in the neutralized waste waters.Environmental impacts associated with in-situ leaching of ion-adsorption type deposits.

5.4.1 Effects on ore body and lower-lying agricultural areas

The in-situ leaching practice requires less surface vegetation clearing than the previously practiced tank/heap leaching techniques, but increases the risks of mine collapses and landslides (Yanfei et al., 2016; Yang et al., 2013). In the leaching process, Ca and Mg cations situated “alongside” REE on the surface of the ore minerals are unintentionally replaced with ammonium ions, which causes soil nutri-

[17] Around 10-15% of the organic phase is lost annually Elwert (2017a). Different sources provide losses for estimates in relation to the production output, where around 1kg -

ent depletion (Yanfei et al., 2016). Sulfate ions contained in the leachate are also emitted into the ore body[18]. In humid regions, sulfate ions are taken up by soils through three main mechanisms: immobilization through microbial activity in the top soil layer; where the ions are built into organic compounds, adsorption to the surface of soil particles, usually associated with the release of OH^- or H_2O ions to the solution, or precipitation of insoluble aluminum sulfates (Sokolova and Alekseeva, 2008). Adsorption is likely to be the most relevant mechanism in the section of the ore body from where the rare earths are extracted. Ion-adsorption clay deposits are often found in hilly landscapes, with surface areas of the deposits themselves generally unsuitable for agriculture. Due to high precipitation volumes in the area, ions are quickly washed out from the ore body itself. Ammonium emissions contribute to the eutrophication of nearby fields.

5.4.2 Effects on ground- and surface water near the mining site

Both ammonium and sulfate ions affect freshwater ecosystems. High concentrations of ammonium have been reported for the ground- and surface water near ion-adsorption clay deposits (Yang et al., 2013). Vahidi et al. (2016) and Yanfei et al. (2015) highlight eutrophication associated with direct emissions of ammonium. According to ILCD, nitrogen (N) emissions contribute to marine eutrophication, whereas freshwater eutrophication is limited by phosphor (EC -JRC, 2010). This is reflected in the recommended method pack, which only incorporates phosphor emissions for the freshwater eutrophication category. Terrestrial (soil) eutrophication takes into account N emissions to air only. N emissions to freshwater, ground and marine waters (but not soil) are captured by the characterization factors for marine eutrophication. A quick review of the literature was undertaken to find out if these assumptions are valid in the Chinese context. Eutrophication is a problem in Chinese lakes, estuarine and coastal regions (Conley et al., 2009; Le et al., 2010; Strokal et al., 2014). According to the literature, the growth of algae is not always strictly limited by P in Chinese lakes (Yi et al., 2014). Eutrophication assessments in Chinese lakes consider both N and P content; and significant regional differences of algae communities to different nutrients are reported (Huo et al., 2013). According to Conley et al. (2009), who assessed eutrophication alleviation in an international context, site-specific factors need to be considered, and a balanced approach to control both P and N is required. Hence, the generic eutrophication category from CML was used for the assessment, which takes into account emissions of P and N to different soil, water, and air compartments.

Effects of emissions from mining activities on surrounding water bodies are reported in the literature. Secondary (anthropogenic) salinization of rivers in mining areas is known to reduce aquatic biodiversity and disturb freshwater ecosystem functions, e.g. reducing the breakdown of organic matter (Cañedo-Argüelles et al., 2013) (see also (Linarić et al., 2013). Sulfate ions in particular stimulate the microbial production of HS^- ions, which are phytotoxic, and contribute to eutrophication (by inhibiting nitrification and by contributing to the release of phosphor) (Cañedo-Argüelles et al., 2013).

Heavy metals are mobilized from soils at acidic pH levels (Tekedil Zeenat Humsa, 2015) - the pH of the leachate is around 3 (Chi et al., 2003). According to one study, high levels of heavy metals have been reported in waste water from ion-adsorption clay deposits (Vahidi et al., 2016; Yang et al., 2013). Fe^{3+} and small amounts of Fe^{2+}, Mn^{2+}, and Pb^{2+} can be found in the leachates (Chi et al., 2003; Jun, 2011). Fe^{2+}, Mn^{2+}, and Pb^{2+} are toxic to humans and aquatic organisms.

With ore grades decreasing, the leaching recovery rates are getting lower, which means that higher amounts of ammonium salts are used and potentially emitted, exceeding emission standards by far (Krishnamurthy and Gupta, 2016; Tian et al., 2013). Research is being conducted in China to improve

[18] In ultisols, a soil type found in Southeast China and mentioned in the literature in the context of ion-adsorption clays Cocker (2012); University of Idaho, up to 24.4 mmol of sulfate ions /kg soil can be absorbed (for conditions with sulfate concentrations in the leachate between 3 and 20 mmol/l) Sokolova and Alekseeva (2008).

the recovery rates, decrease chemical consumptions and emissions in the in-situ mining process. One study has looked into additives which help make the lixiviant (leachate) more hydrophilic and to help diffusion through the ores, which are characterized by small porosity and low permeability (Tian et al., 2013). The permeability also poses a barrier to using more concentrated ammonium sulfate solutions (which might otherwise be a means to increase the recovery rates). Another study suggested the replacement of the precipitation step with a technique involving SX, ion exchange and a liquid membrane (Jun, 2011). Both options are said to improve the efficiency and reduce the environmental impacts of the process. Alternatives to ammonium sulfate reagents for the ion-exchange process are also a research topic in China (Yanfei et al., 2015).

5.4.3 Environmental impacts associated with the solvent extraction process

After the in-situ mining and processing stage, four extraction systems are currently combined in SX, resulting in high levels of chemical consumption and emissions (Chun-Sheng et al., 2016). It has been suggested to work with only one extraction system, namely P507, to enable the recirculation of both phases (aqueous and organic) ("hyperlink process"), which would decrease chemical consumption and emissions during rare earth separation (Chun-Sheng et al., 2016). Also, some losses of the organic phase are unavoidable due to its volatility. Water usage /emissions are above the required standards in current mining practice (Chun-Sheng et al., 2016). There is also an economic motivation to decrease water usage in the industry, due to the high expenditure (Leveque, 2014). Salt concentrations in the waste water are also an issue because the separation process is undertaken inland and effluents are hence emitted to freshwater (Chun-Sheng et al., 2016; Leveque, 2014). Salinization negatively affects aquatic biodiversity (Cañedo-Argüelles et al., 2013).

5.5 Life cycle assessment of rare earth oxide production from ion-adsorption clay deposits

5.5.1 Goal, scope, functional unit and system boundaries

The goal of this study is to compile a dataset representative of the typical rare earth oxide production process from ionic deposits in Southern China which can be used in future studies. Due to uncertainties associated with the dataset, recommendations for further research to improve the estimate for environmental impacts are provided.

The **functional unit** for the compiled dataset is the production of one metric ton of separated rare earth oxides after solvent extraction. The datasets reflects an estimate for a production situation in which all individual rare earth elements are separated. The functional unit corresponds to one metric ton of separated rare earth oxide with the rare earth composition of the ore, given in Table 6. (It is assumed that the full separation of Ho_2O_3, Tm_2O_3, Yb_2O_3, and Lu_2O_3 into individual elements is not conducted, due to the currently low demand for these elements). Separate inventories for individual rare earths are not presented, since this was not the aim of the study – see section 5.7.3 on assigning impacts to individual REEs.

The **system boundaries** comprise in-situ leaching from ion-adsorption deposit ores in Southern China, and separation into individual rare earth oxides, starting with the obtained concentrate. A description of the process comprised in the functional unit is given in 5.3.1 and 5.3.3.

5.5.2 Life cycle inventory analysis

The life cycle inventory was compiled from the literature and complemented with information obtained in expert interviews conducted in April and July 2016. The dataset comprises the mining and separation of the rare earth concentrate into individual rare earth oxides, and is presented both per metric ton of REE concentrate and per metric ton of separated REO. 0

Vahidi et al. (2016) present life cycle inventory data for in-situ leaching of rare earths from ionic deposits, but do not include the production of individual rare earth oxides through solvent extraction (Figure 9). This part to the life cycle inventory was added - largely based on material requirements and emissions reported in Chun-Sheng et al. (2016). Amendments to the data for the in-situ leaching part are presented below.

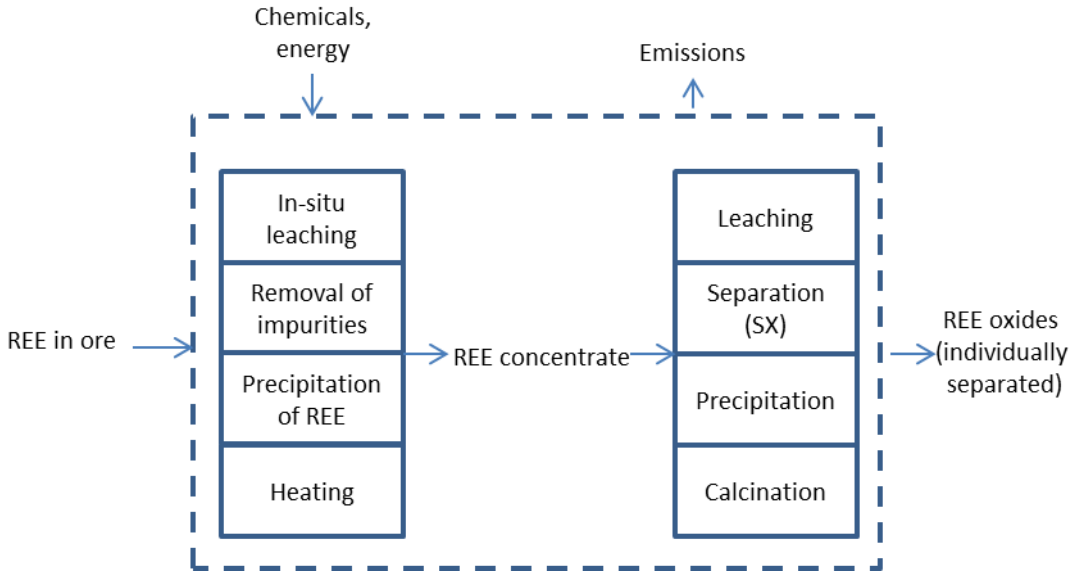

Figure 9: System boundaries LCI: In-situ leaching of REE from ionic deposits and separation of REE concentrate into individual REE oxides

Additions and modifications to the in-situ leaching dataset presented by Vahidi et al. (2016)

For the mining part, the dataset was largely adopted from Vahidi et al. (2016). The dataset is shown in Table 8 and Table 9.

Relating low and high LCI values to ore grades

Material and energy requirements are a function of ore grades. It was assumed that the high consumption figures presented in the dataset by Vahidi (2016) refer to the lower end of the economically viable ore grade, and the lower consumption figures to the higher end of the ore grade. This is a rough assumption which is not based on a quantitative model to describe the relationship between ore grades and energy and material efficiencies, but done to highlight the issue of high grading / mine sterilization and depleting ore grades.

Furthermore, the rare earth recovery rate is also a function of the ore grade (which is again related to the material and energy requirements). For the low impact estimate, the higher recovery rate is assumed, and vice versa. Mining is economically viable for concentrations around 0.2-0.4% (Ding, pers. comm.). The reference unit of the output in Vahidi et al. (2016) corresponds to 91% REO and 9% impurities (functional unit: 1kg of 90-92% purity mixed REO). Of the 910g REO per kg output, the metal content is 764g. The (maximum) accessible fraction of rare earths in the deposits, adsorbed to the

clays in ionic form, amounts to approximately 80% of total rare earth content (Krishnamurthy and Gupta, 2016). Overall, a 40% to 70% recovery of the accessible REE content was assumed for this dataset.

Elementary /resource flows

Estimates on resource depletion; amount of material excavated (from boreholes and ponds) produced and land occupation were calculated, based on the recovery rate and ore grade range assumptions, ore density and geometry of the mined deposits, as described in the literature. An average composition of REE in ion-adsorption clay deposits is given, representative of the output from the major producing mines, and based on the most recent source (Table 6).

To account for resource depletion, the elementary flows are modelled for 100% of the ore content, since it is assumed that after mining, the remaining content is no longer viable to mine in the near future. For the aluminosilicate fraction of the clay, the resource consumption is assumed to be that of kaolinite – in practice, there are a variety of minerals present in the ores (Tian et al., 2010). The quantity of drilling slurry, from which no rare earths are extracted, is estimated based on Yang (2013), who gives typical sizes of drilling holes and distances between them. The area mined per metric ton of REO is estimated based on ore density and depth of the regolith layer from Yanfei et al. (2016) and Yang et al. (2013), respectively. Estimates were added for the area required for the ponds and the storage for the excavated materials from the ponds and ore drillings.

Process energy consumption during in-situ leaching

Estimates for electricity presented in the dataset were maintained. The authors state that the large range presented (0.5-5.3 MWh/t REO), which they have calculated from electricity costs for the mines reported in Chinese literature, is likely to be associated with the specific site conditions and the associated differences in the electricity requirements for the pumps. The energy consumption for heating of carbonates is likely to consume energy quantities in the same magnitude as the calcination step in the separation process. This figure in the dataset was adjusted as follows: The energy carrier used for the heating of the carbonates was assumed as heavy fuel oil. Alternatively, natural gas or coal could be used. Since it is unclear whether the energy consumption estimate for filtering and mechanical pressing has been included within the electricity consumption estimate, and the processes might be run with other energy carriers, 20% of the energy consumption estimate for the heating of the carbonates was added for the low estimate, and 50% for the high estimate (6-7.5 MWh/t rare earth concentrate). The energy consumption for site preparation is covered by the excavation dataset.

Precipitating agents and CO_2-release from precipitation

Ammonium bicarbonate is commonly used for the precipitation of rare earths before separation (Lartigue-Peyrou, 2016; Vahidi et al., 2016). It was therefore assumed that only ammonium bicarbonate is used in this step, and dataset was adjusted accordingly to account for the associated material usage and emissions.

Chi et al (2003) provide a detailed analysis of the ammonium bicarbonate consumption during precipitation. Using the formulae given in Chi et al (2003), an ammonium bicarbonate consumption per t REO concentrate of around 3-4 metric tons was calculated for the impurity percentage reported in Table 7, as well as for an assumed double impurity content. The estimate includes ammonium carbonate consumption as reagent, pH regulator and reagent for carbonic acid decomposition for both impurity removal precipitation and rare earth precipitation. The consumption is influenced by the REE recovery rates during precipitation.

Direct CO_2 emissions from precipitation of impurities and removal of carbonic acid and heating of carbonates were added. The quantities of CO_2 emitted in the process depend on the ratio of impurities / REE, REE recovery rates and the reagent used. Direct CO_2 emissions are in the range of 1t per metric ton of rare earth concentrate.

Table 7: Composition of leachates from different ion-adsorption deposit ores in mmol /l (Chi et al., 2003)

Mine[19]	REE	Al	Fe	Mg	Ca	pH
ND	39	4.4	4.1	0.26	2.1	3.6
WP	41	4.8	4.3	0.42	2.4	3.4
JN	38	4.2	3.7	0.3	3.1	3.5
GL	37	4.5	3.9	0.32	2.8	3.5

The actual composition varies. According to Jun (2011), the leach liquor typically contains $(NH_4)_2SO_4$ (~2000 mg/L), Al^{3+} (~1000 mg/L), and Ca^{2+} (~1000 mg/L), Fe^{3+} (~100 mg/L).

Ammonium sulfate consumption and emissions

The ammonium sulfate estimate given by Vahidi was interpreted as the ammonium sulfate weight, not the weight of the N content as presented in the dataset. This interpretation is based on the emission quantities given in the dataset. The net usage of ammonium sulfate is dependent on the recovery rate and ore grade, but most importantly on whether the leachate is captured and reused at another site when the mining operation ceases (Figure 7). The dataset given by Vahidi assumes that the waste water is emitted, with or without prior removal of NH_4^+ ions.

An extra column was added in Table 8 and Table 9 to model the reuse case. In the reuse situation, the NH_4^+ input during precipitation corresponds approximately to the magnitude of NH_4^+ losses to the ore body, suggesting a net usage of $(NH_4)_2SO_4$ could be low, or close to zero if infinite reuse was possible in practice, (which seems unlikely). As a rough estimate, one third of the lower $(NH_4)_2SO_4$ figure for the reuse situation was assumed. In all three modelled cases, approximately 20% of the leachate is lost in the ore, and some leachate is spent on ion exchange for the unintended extraction of impurities.

Emissions to soil have been calculated by Vahidi from the ion exchange equation and relate to the corresponding quantity of rare earths extracted. Since NH_4^+ ions also exchange other metal ions, for a rough estimate, 30% for the emissions to soil were added, based on the composition in Table 7. It is assumed that the difference between chemical input, NH_4^+ emissions and leachate losses, and possible leachate reuse is emitted to water (it should be noted that it does not make a difference whether ammonium ions are emitted to soil or water in the “generic eutrophication” impact assessment method from CML).

Ammonium bicarbonate - consumption and emissions

The ammonium bicarbonate consumption was calculated based on the equations given in Chi et al. (2003). The figures (3-4 t NH_4HCO_3 per metric ton REO) are in line with the figures given by Vahidi (2.2-4.5 t/t).

Estimate for Al^{3+} emissions to freshwater

One of the main impurities in the leachate is aluminum (Luo et al., 2015), a constituent of the clay minerals (Voßenkaul et al., 2015) which is unintentionally extracted in the ion exchange process. Since the

[19] Ningde (ND), Wuping (WP), Jianning (JN),and Qingliu (QL), four ion-adsorption clay mines in China (Chi et al. (2003))

process of impurity removal is not 100% efficient, some of the ions remain in the leachate. It is, however difficult to derive estimates for Al emissions since the process is continuous with changing conditions during the course of the mining operation. The leachate is continuously recirculated in the in-situ leaching process, until the rare earth quantities extracted become too low to make the mining operation worthwhile (Ding, pers. comm.) – i.e. the concentrations of rare earths and impurities decrease during the operation time of the mine. The ratio of individual elements extracted to the leachate is different for different ore grades, as higher quantities of impurities are extracted from lower ore grades, and also due to the geological variability of the deposits.

An estimate for Al^{3+} emissions was derived as follows: 95% of Al^{3+} ions are typically removed during precipitation before the concentrations get too low, i.e. 5% are potentially emitted (Luo et al., 2015). The mass ratios between Al^{3+} and RE^{3+} ions are around 1:10 (Chi et al., 2003) to 1: 16 Al^{3+}:RE^{3+} (Luo et al., 2015). If the leachate is fully emitted to surface waters with the remaining 5% Al^{3+}, this corresponds to 3-5 kg Al^{3+} ions per metric ton of REO concentrate.

Table 8: LCI: Inputs per metric ton of REO concentrate production from ion-adsorption clay deposits, in-situ leaching, with 91% purity

Flow	Unit	Low estimate with leachate reuse	Low estimate	High estimate	Source
Lanthanum	t	0.386	0.386	0.675	Own addition to LCI dataset presented by Vahidi et al. (2016), based on REE composition in deposit (Table 6) with assumptions regarding recovery rates (see subsections of 5.5.2: *Elementary/ Resource flows* and *Relating low and high LCI values to ore grades* for details)
Cerium	t	0.045	0.045	0.079	
Praseodymium	t	0.079	0.079	0.139	
Neodymium	t	0.247	0.247	0.433	
Samarium	t	0.064	0.064	0.113	
Europium	t	0.013	0.013	0.023	
Gadolinium	t	0.085	0.085	0.149	
Terbium	t	0.010	0.010	0.017	
Dysprosium	t	0.053	0.053	0.093	
Holmium, Thulium, Ytterbium, Lutetium	t	0.034	0.034	0.059	
Erbium	t	0.036	0.036	0.062	
Yttrium	t	0.314	0.314	0.549	
Kaolinite, 24% in crude ore, in ground	t	340	340	1193	
Water, unspecified natural origin	m^3	1000	1000	1000	Vahidi et al. (2016)
Occupation, mineral extraction site	m^2*a	0.017	0.017	0.174	own estimate, based on Yang et al., (2013) and Yanfei et al., (2016)
Transformation, to mineral extraction site	ha	0.009	0.009	0.17	

Market for excavation, hydraulic digger | excavation, hydraulic digger - GLO[20]	m^3	1100	1100	1200	Vahidi et al. (2016)
Market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised - GLO	t	0.09	0.09	0.1	Vahidi et al. (2016)
Market for limestone, crushed, for mill | limestone, crushed, for mill - GLO	t	0.004	0.004	0.006	Vahidi et al. (2016)
Market for ammonium sulfate, as N | ammonium sulfate, as N - GLO	t	0.4	1.29	2.20	own calculation based on Vahidi et al. (2016) and expert opinion (from industry) – see section 5.5.2 – subsection *Ammonium Sulfate Consumption and Emissions* for details
Market for extrusion, plastic pipes | extrusion, plastic pipes - GLO	t	0.092	0.092	0.100	Vahidi et al. (2016)
Market for sulfuric acid | sulfuric acid - GLO	t	0.300	0.300	0.750	Vahidi et al. (2016)
Market for ammonium bicarbonate | ammonium bicarbonate - GLO	t	3	3	4.1	own calculation based on equations in Chi et al. (2013) – please refer to section 5.5.2 – subsections *Ammonium Bicarbonate Consumption and Emissions* and *Precipitating agents and CO2-release from precipitation*

[20] Market processes are suitable when detailed information regarding the production process is not available. Contrary to the datasets reflecting a specific production route, market datasets account for impacts of transportation. Besides that, there are no differences for global datasets. On a regional level, the production mix may however be different to the market mix. (The market mix represents the difference between imports minus exports – see https://www.ecoinvent.org/support/ecoinvent-forum/topic.html?&tid=339 und https://support.simapro.com/articles/FAQ/What-is-the-difference-between-ecoinvent-market-and-transformation-processes)

Heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas - RoW	MWh	6	6	7.5	own estimation based on expert opinion – please refer to section 5.5.2 – subsection *Process energy consumption during in-situ leaching*
Market group for electricity, medium voltage | electricity, medium voltage - CN	MWh	0.53	0.53	5.3	Vahidi et al. (2016)

Table 9: LCI: Outputs per metric ton of REO concentrate production from ion-adsorption clay deposits, in-situ leaching, 91% purity

Flow	Category	Unit	Low estimate with leachate	Low estimate	High estimate	Source
REO concentrate production from ion-adsorption deposits, in-situ leaching, 90% purity	T Eigene Flüsse/primaerproduktion RE	t	1	1	1	N/A – reference flow
Sulfate, ion	water/fresh water	t	1.57	4.72	8.28	own calculation based on scenarios – see section 5.5.2, subsection *Ammonium Sulfate Consumption and Emissions* for details
Sulfate, ion	soil/unspecified	t	0.4	0.4	1.5	
Ammonium, ion	soil/unspecified	t	0.35 +0.2	0.35 + 0.2	0.35 + 0.6	own calculation based on scenarios – see section 5.5.2, subsections *Ammonium Sulfate Consumption and Emissions and Ammonium bicarbonate - consumption and emissions* for details
Ammonium, ion	water/unspecified	t	0.56	0.26	3.44	

Flow	Category	Unit	Low estimate with leachate	Low estimate	High estimate	Source
Carbon dioxide, fossil	air/unspecified	t	0.8	0.8	1.1	own calculation based on Equ. 6 and 7 – see section 5.5.2, subsection *Precipitating agents and CO_2-release from precipitation*
Aluminum ions	water/fresh water	t	0.003	0.003	0.005	own calculation based on various literature sources – see section 5.5.2, subsection *Estimate for Al^{3+} emissions to freshwater*

Solvent extraction – transforming rare earth concentrate to individual REE oxides

Energy and material efficiency in solvent extraction

The concentration of the input solution has an important influence on the process efficiency which can be achieved and affects the required size of the equipment (Leveque, 2014), (Ding, pers. comm). Rare earth loadings of up to~180g REO /l in the solvent or extractant are possible, but 50g/l are more common. The loading capacity depends on the system used.

The process can be targeted to the required output and purity (Leveque, 2014). The number of processing stages required in SX depends on the extractant used, which determines the separation factor between individual rare earth elements, and therefore the number of processing steps required (Leveque, 2014). As mentioned in section 5.4, the use of different extraction systems for different parts of the system decreases the overall number of separation steps required (and process energy consumed by the mixer settlers per metric ton of output), but results in a higher consumption of reagents and consequently higher emissions per unit of output (Chun-Sheng et al., 2016). Another important factor which influences the energy consumption is whether and how much heating is required to achieve the required processing temperatures. To reach a purity for individual rare earths between 99 and 99.999%, ~30 to 100 separation stages are required to separate two groups of rare earths, or individual rare earths (Leveque, 2014). The separation of heavy rare earths is generally more complex than the separation of light rare earths, and associated with a larger number of processing steps (Leveque, 2014).

Life cycle inventory compilation

For the solvent extraction process which follows after in-situ leaching, the inventory is based on the process described in Chun-Sheng et al. (2016) which is commonly applied for the separation of rare earths from ionic deposits in China – (see also Krishnamurthy and Gupta, 2016). The available information does not allow a detailed analysis of the different aspects discussed in 5.4, but represents an estimate.

The consumption of chemicals used in SX of REE separation from ion-adsorption clay deposits is based on Chun-Sheng et al. (2016). The source does not provide a detailed analysis of chemical usage; so estimates regarding the quantities of different reagents had to be made. Overall quantities of acid, neutralizing agent, water and emissions are presented in the document. For water usage and emissions, 30 m^3/ t REO was used as a rough lower estimate of consumption and emission (based on the Chinese emission standard), 107 m^3/ t REO for the higher consumption estimate and 120 m^3/ t REO for the higher emission estimate (based on typical process values) (Chun-Sheng et al., 2016). The input - output difference may be down to the water content in the diluted acid. The oxalic acid consumption and CO_2 emissions arising from the calcination were estimated based on chemical equations (Equ. 6 and 7). Oxalic acid is modelled as citric acid – (Table 10) see also Vahidi et al. (2016). Besides oxalic acid, HCl is used in the SX process. The difference to the total acid consumption stated by Chun-Sheng et al. (2016) was assumed to be HCl, and the neutralizing agent used in the process to be NaOH. Based on a rough comparison of inputs and outputs for Cl and Na, it was assumed that the input quantity for acid used during extraction given in Chun-Sheng et al. refers to HCl (30-37%). The quantity of HCl as gas is included as a high estimate; the quantity of HCl 36% is included as a low estimate for the acid consumption. The salt output is adjusted accordingly in the inventory. (However, it should be noted that the emissions of salts are not currently captured by the common impact assessment methods.)

Due to the volatility of the organic phase, some solvent losses are unavoidable. According to Elwert (2017a), losses amount to 10-15 % of the organic phase annually. For the life cycle inventory analysis, the losses per ton of REO are of interest. The net consumption of the organic phase (P507, kerosene, other extractants) is estimated at 1kg-20kg /ton of REO (Vahidi and Zhao, 2016) and Ding, pers. comm.). According to the data presented by Vahidi (2016) and Schmidt (2013); the net consumption for the extractant is 30-35 kg/ t REO for a different route. The impact assessment results from Vahidi and Zhao (2016) for P204, a different extractant which is commonly used for the separation of light REE, indicates that the impact of the solvent losses is not negligible. The authors only present impact assessment results, not the LCI dataset itself. The impacts are around 50 times of "solvent, organic at plant" for GWP, and in this range for most other impact categories. To obtain an own estimate, a dataset was constructed as a proxy for P204, which is manufactured by reacting phosphorus pentoxide with 2-ethylhexanol (Equations 10 and 11).

$$4\ C_8H_{17}OH + P_4O_{10} \rightarrow 2\ [(C_8H_{17}O)PO(OH)]_2O \quad \text{[Equation 10]}$$

$$[(C_8H_{17}O)PO(OH)]_2O + C_8H_{17}OH \rightarrow (C_8H_{17}O)_2PO(OH) + (C_8H_{17}O)PO(OH)_2 \quad \text{[Equation 11]}$$

This is done by using the closest proxy datasets for the reactants available in ecoinvent. Phosphorus (process: market for phosphorus, white, liquid | phosphorus, white, liquid | APOS, U) is used as precursor for P_4O_{10}. The oxidation of phosphorus is exothermic and therefore does not need any further energy input. 1-Butanol (process: market for 1-butanol | 1-butanol | APOS, U) is used as a proxy for butanal (the aldehyde form of butanol). The process yield was based on Li (2009) and own estimates: 45% for the last synthesis step to Di-(2-ethylhexyl)phosphoric acid, 80% yield for the hydrogenation and 80% yield for the aldol condensation. Process energy consumption and infrastructure was adopted from organophosphorus-compound production, unspecified | organophosphorus-compound, unspecified | APOS, U for an estimate. Impacts of the net solvent are very small (<1.5% in each category and for each scenario).

During SX, electricity is used for stirring and pumping. The rare earths are first separated into groups of REE with similar properties which are then further separated into individual rare earth fractions. Individual RE fractions are then calcinated to obtain REO. The energy consumption for the full SX process is in the same order of magnitude as the consumption for the calcination process (Ding, pers. comm.). According to Talens Peiro, (2013), the energy consumed for SX is between 4 and 6 MWh /t REE. In this study, 5 MWh/t REO were assumed.

Table 10: Inputs SX and calcination (from RE concentrate from ion-adsorption clay deposits) per metric ton of REO, composition according to Table 6, separated into individual rare earths

Flow	Category	Unit	Low estimate	High estimate
Water, deionized, from tap water	resource/in water	m^3	30	107
P204	T Eigene Flüsse	t	0.001	0.02 (1)
Spent solvent mixture | clinker production – RoW (modelled as input)	239: Manufacture of non-metallic mineral products n.e.c./2394:Manufacture...	t	0.001	0.02 (1)
Market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state – GLO	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, ...	t	2.5	3.4

REO concentrate production from ion-adsorption clay deposits, in-situ leaching, 91% purity	T Eigene Flüsse/primaerproduktion RE	t	1.13	1.13
Market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state – RoW	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, ...	t	3.36	9.33
Market group for electricity, medium voltage | electricity, medium voltage - CN	351: Electric power generation, transmission and distribution/3510:Electr...	MWh	5	5
Market for citric acid | citric acid – CN (citric acid is modelled to represent oxalic acid usage)	201:Manufacture of basic chemicals, fertilizers and nitrogen compounds, ...	t	1.02	1.23
Heat, district or industrial, other than natural gas | heat production, heavy fuel oil, at industrial furnace 1MW - RoW	3530: Steam and air conditioning supply/3530a: Steam and air conditioning...	MWh	5	5

Table 11: Outputs SX (from RE concentrate from ion-adsorption clay deposits), per metric ton of REO, composition according to Table 6, separated into individual rare earths

Flow	Category	Unit	Low estimate	High estimate
Sum of REO produced from SX after in-situ leaching from ion-adsorption clay deposits	Own category/REE primary production	t	1	1
Metal content, sum of REO produced from SX after in-situ leaching from ion-adsorption clay deposits		t	0.84	0.84
Sodium	water/fresh water	t	1.44	1.97
Chloride	water/fresh water	t	3	9
Water, process, unspecified natural origin	water/unspecified	t	30	120
Carbon dioxide, fossil	air/unspecified	t	0.84	0.84

5.6 Impact assessment results

The life cycle impact assessment results were calculated with the CML baseline method. The modelling was done with OpenLCA and ecoinvent 3.2 background datasets. Results are presented here for attributional background datasets with “APOS” allocation to enable a comparison of the impact assessment results from other published datasets. The resource depletion category was adjusted to include characterization factors for REE.

Impact assessment results are presented per metric ton of separated rare earth oxide for a low and a high estimate scenario, and a “leachate reuse” scenario (Table 12). The leachate reuse scenario provides similar results to the “low estimate” scenario. A lower input of ammonium sulfate per t REO concentrate, and adjusted sulfate and ammonium emissions, constitute the only differences made to the “low estimate scenario” life cycle inventory. The largest difference at life cycle impact assessment level appears in the generic eutrophication category, which indicates that the management of leachate emissions is crucial for the impacts in this category. Besides eutrophication, the other category impacts

are slightly lower under the “leachate reuse” scenario, due to the partially avoided ammonium sulfate production.

5.6.1 CML baseline, with ADP category adjusted

Table 12: CML baseline results per metric ton of REO from ion-adsorption clay deposits, separated, after solvent extraction

Impact Assessment category	Low estimate (leachate reuse scenario)	Low estimate scenario	High estimate scenario	Unit
Acidification potential - average Europe	192	204	319	kg SO_2 eq.
Photochemical oxidation - high NOX	8.2	8.8	14	kg ethylene eq.
Terrestrial ecotoxicity - TETP inf	283	308	482	kg 1.4-dichlorobenzene eq.
Ozone layer depletion - ODP steady state	0.007	0.007	0.013	kg CFC-11 eq.
Depletion of abiotic resources - fossil fuels	356.4	377.5	588	GJ
Human toxicity - HTP inf	22.4	20.5	35.3	t 1.4-dichlorobenzene eq.
Depletion of abiotic resources - elements. ultimate reserves	0.27	0.29	0.51	kg antimony eq.
Freshwater aquatic ecotoxicity - FAETP inf	11211	12195	20270	kg 1.4-dichlorobenzene eq.
Marine aquatic ecotoxicity - MAETP inf	39742	42348	71385	t 1.4-dichlorobenzene eq.
Eutrophication – generic	471	928	1719	kg PO_4--- eq.
Climate change - GWP100	31.4	33.2	53.1	t CO_2 eq.
Depletion of abiotic resources - elements. economic reserves	57	58	114	kg antimony eq.

5.6.2 Normalized results

Normalization is used to compare the results of an analysis to the total impact occurring in a specific region for a certain impact category within a reference year (Benini et al., 2014). The CML normalization sets are calculated by multiplying the annual emissions of the reference substances by the respective characterization factors. When comparing the life cycle impact assessment results of the separated REO production to a normalization set (“world 2000”), it is striking that the marine ecotoxicity category has by far the highest normalized contribution in all three scenarios. With a distance, this is followed by human toxicity, then freshwater ecotoxicity and generic eutrophication. The marine ecotoxicity, human toxicity and freshwater ecotoxicity impacts originate upstream from chemical and energy production. Eutrophication is caused by ammonium emissions at the in-situ leaching site.

Table 13: CML baseline results normalized to "World 2000" impact set (impact of 1 metric ton separated REO/ estimated global impact for respective category in year 2000)

Impact assessment method	High estimate scenario	Leachate reuse scenario	Low estimate scenario
Marine aquatic ecotoxicity - MAETP inf	3.68E-07	2.05E-07	2.18E-07
Human toxicity - HTP inf	1.36E-08	7.94E-09	8.70E-09
Eutrophication - generic	1.0853e-8	2.97E-09	5.859e-9
Freshwater aquatic ecotoxicity - FAETP inf	8.57E-09	4.74E-09	5.16E-09
Depletion of abiotic resources - elements. ultimate reserves	2.44E-09	1.28E-09	1.38E-09
Depletion of abiotic resources - fossil fuels	1.55E-09	9.38E-10	9.93E-10
Acidification potential - average Europe	1.34E-09	8.03E-10	8.52E-10
Climate change - GWP100	1.27E-09	7.50E-10	7.92E-10
Terrestrial ecotoxicity - TETP inf	4.41E-10	2.59E-10	2.81E-10
Photochemical oxidation - high NOx	3.76E-10	2.23E-10	2.39E-10
Ozone layer depletion - ODP steady state	5.71E-11	3.02E-11	3.09E-11

5.6.3 Contribution analysis for selected impact categories

A contribution analysis is shown for GWP 100a, eutrophication and abiotic resource depletion (ADP).

GWP 100a

The GWP-100a values for the production of 1t of individually separated REO produced through the analyzed route range from 31-53 t CO_2 equ./ t REO. A contribution analysis for the global warming potential (GWP100a) shows that both mining (concentrate production) and SX are important production stages, with around 33-42% of GWP-100a attributable to the production of the concentrate. Details can be found in Annex to this Chapter (Tables 1-3, Annex A2). Around 31-33% of the GWP-100a is down to process energy consumption, around 4-6% is direct emissions from CO_2 releases during precipitation and calcination, and the remainder is from the upstream impacts of chemical inputs.

When compared to the production of REE from deposits rich in light REE, the GWP100a values per metric ton of separated REO are higher for the production of REO from ion-adsorption clay deposits. Values per metric ton of separated REO for the production of predominantly light rare earths from Bayan Obo are around 15-35 t CO_2 equ./ t separated REO after SX (Sprecher et al., 2014b). According to Zaimes et al. (2015), the production of 1t of separated REO from Bayan Obo ranges from 23-35 t CO_2 equ./ t REO. The ranges presented account for process- specific differences between the extraction of light, medium and heavy rare earths.

Eutrophication

The generic eutrophication potential for 1t REO, separated by individual REO, after SX, amounts to 0.5- 1.7 t PO_4^--equ./ t REO. 92% (leachate reuse scenario) to 96% (high estimate scenario) of this potential is attributable to the production of the RE concentrate. Of that, 90-95% can be attributed direct process emissions of NH_4^+ to soil and freshwater. The generic eutrophication category by CML has the same characterization factors for ammonium ion emissions, regardless of the receiving com-

partment. The generic eutrophication potential of in-situ leaching is significantly lower when the leachate is reused, or when wastewater emission standards are maintained.

Abiotic resource depletion

The impact assessment category “CML baseline, V.4.4.” of January 2015, implemented in OpenLCA method pack, version 1.5.5, which addresses the depletion of non-renewable resources, was adjusted to include characterization factors for rare earth elements. The lack of some characterization factors for rare earths in the ADP assessment method has been pointed out by Sutter and Merz (2015) and Walachowicz (2014) who derived characterization factors for dysprosium and neodymium. (The ILCD midpoint method, category ADP reserve base, contains characterization factors for rare earths, but they are generic for all REE (except for yttrium, which has been assigned a different factor) (JRC, 2013)). The depletion potential is a function of the resources available, (i.e. the concentration in the earth’s crust at concentrations for which economic extraction is currently or potentially feasible (see (USGS, 2016c)) multiplied by the mass of the earth’s crust), and the annual extraction rates. For each element, the annual production figure is divided by the reserves squared; and the value is then divided by the corresponding ratio for antimony, which serves as reference substance for this impact category (EC -JRC, 2010).

The concentrations were adopted from USGS (2010), in accordance with the figures for other elements (EC -JRC, 2010). The mass of the earth’s crust was taken from Guinée (1995), (2.31×10^{22} kg). The rare earth production figures were adopted from EC (2014) and correspond to the global production in the year 2012 (converted to metallic weights).

Table 14: ADP characterization factors for REE and kaolinite (ultimate reserve base and economic reserves)

Elementary flow	ADP factors, ultimate reserve base, kg antimony equivalent / kg REM	ADP factors, economic reserve base, kg antimony equivalent / kg REM
Lanthanum	2.40E-05	2.10E-03
Cerium	7.58E-06	8.90E-04
Praseodymium	6.28E-05	1.08E-02
Neodymium	1.31E-05	3.23E-03
Samarium	3.41E-05	1.63E-02
Europium	1.46E-04	8.07E-02
Gadolinium	3.65E-05	2.09E-02
Terbium	1.44E-04	8.37E-02
Dysprosium	3.58E-05	1.98E-02
Holmium	1.75E-04	1.00E-01
Thulium	1.34E-03	1.61E+00
Ytterbium	3.11E-05	3.102E-02
Lutetium	4.42E-04	1.60E+00
Erbium	4.40E-05	2.24E-02
Yttrium	4.85E-06	5.33E-03

According to the impact assessment results (ultimate reserves, not shown here), the rare earth elementary flows contribute with around 15% to the category; indicating that they are relatively abundant in the earth’s crust. The largest contributor to the impact category is sodium chloride.

Characterization factors for REE for “ADP, economic reserves” were calculated, based on figures provided by Krishnamurthy and Gupta (2016) and EC (2014) for REE and USGS (2016) and van Oers et al.(2002) for reserves and annual extraction rates of antimony. Economic reserves constitute the part

of the reserve base which can be economically extracted. Known reserves are largely from primary deposits in which the REE are contained in minerals - LREE-rich mineral deposits (~80% bastnaesite, 20% monazite) (Krishnamurthy and Gupta, 2016). The composition of the reserve estimate reflects this. The reserve base for ion-adsorption clay deposits, the currently most relevant deposit type for REE mining, is in the range of one to several million metric tons REO for ionic deposits; around 3% of Chinese reserves (Krishnamurthy and Gupta, 2016). An estimated 7% of the reserve base of these deposits is extracted each year (Krishnamurthy and Gupta, 2016 citing Jordens, 2013).

Results for ADP, economic reserves, range from 58 to114 kg Sb- equivalent per metric ton of separated REO. The rare earths contribute to “ADP, economic reserve base” with 67% (high estimate scenario) to 76% (low estimate scenario). The contribution from individual rare earths to this category does, however, *not* correspond to REE criticality: Thulium and lutetium dominate the contribution to this category at 47-53% for the two elements. These elements are amongst the geologically least abundant REE, but do not currently play an important economic role (EC, 2014). The issue that needs to be highlighted here is that the ADP factor by definition is based on annual extraction rates, rather than annual demand for the metals. In the case of thulium, holmium, lutetium and ytterbium, the supply-demand imbalance is striking, with around 75 metric tons used and 1740 metric tons extracted annually (EC, 2014). These observations support previous observations by Adibi (2014), who compared ADP values for REE production against those of copper production and highlighted that REE criticality was not reflected by the results.

Kaolinite contacted with the leach solution was included in the life cycle inventory, since it is not sure if the clays could still be used for other purposes after the RE mining operation. The result showed a) contribution from kaolinite of 21% for the low estimate and 14% for high estimate scenario). Clay reserves are generally large (USGS, 2016b).

5.7 Discussion, conclusions and recommendations for further work

5.7.1 Main findings

A life cycle inventory for the production of individual rare earth oxides from ionic deposits through in-situ leaching and solvent extraction was constructed. The inventory compilation was based on data from the literature and help from rare earth industry experts. The in-situ leaching data was largely adapted from Vahidi (2016). The system boundaries of the dataset presented here cover the separation of the concentrate into individual oxides, and both steps are shown to contribute significantly to the LCIA results. Life cycle inventory data for the separation process was based on data representative of typical process consumption for solvent extraction in China, starting with concentrates from ion-adsorption clay deposits.

LCIA results, calculated with the CML baseline method, are presented per metric ton of separated REO. Marine ecotoxicity is the category with the largest normalized results (normalized to 'world 2000'); followed by eutrophication and other toxicity categories. Marine, freshwater and human toxicity are all associated with upstream chemical and energy production. Eutrophication is largely caused by direct ammonium emissions at the mining site. The GWP-100a for the production of 1t of individually separated REO produced through the analyzed route ranges from 32-53 t CO_2 equ./ t REO. Of this, 30-40% is attributable to the production of the concentrate with the remainder going to the separation processes.

The influence of ore grades and management practices in the mining process are discussed; and associated impacts on the LCI dataset are estimated. Decreasing ore grades and associated higher impurity- to -REE ratios in the leachate affect the consumption of ammonium bicarbonate used as a reagent during precipitation. This also affects the rare earth extraction efficiency and energy consumption per t of concentrate. The high eutrophication potential associated with ammonium emissions from in-situ leaching (compared with REE production from deposits rich in light REE) has previously been highlighted (Vahidi et al., 2016)The difference between the scenarios for production from ion-adsorption clays shows that this can be greatly reduced with appropriate management practices such as leachate reuse or waste water treatment. Leachate reuse also brings down the net consumption of ammonium sulfate.

When compared to the production of rare earths from deposits rich in light rare earths, the GWP100a values per metric ton of separated REO from ion-adsorption clay deposits tend to be higher, with 15-35 t CO_2 equ. per metric ton of separated REO after SX from deposits such as Bayan Obo (Sprecher et al., 2014b; Zaimes et al., 2015). Findings from a more recent Chinese study by Lee and Wen (2017), where the authors had access to both industry data and Chinese language literature show life cycle impact assessment results per tonne of separated REO from ion-adsorption clays to be of similar magnitude to those shown in this chapter. However, according to their own results for both processing routes, the life cycle impact assessment results per tonne of separated REO are of similar magnitude to those from Bayan Obo for most impact categories. Those findings suggest that previous studies cited here may have underestimated the environmental impact of rare earth production from the Bayan Obo route. It should be highlighted that due to the differences in the REE output mix, the results from different processing routes are, not directly comparable. Furthermore, Lee and Wen (2017) used Chinese background datasets in their modelling, whereas the other studies cited here used ecoinvent datasets. The life cycle inventory assumptions made in this chapter were compared against those made by Lee and Wen (2017) for the most contributing flows, and found to be of similar magnitude for the in-situ leaching and REE concentrate production. The separation process was modeled slightly differently – Lee and Wen modeled a generic solvent extraction process for the separation of REE from all

routes, whereas the life cycle inventory compiled in this chapter represents the solvent extraction process typically applied to the processing of concentrates from ion-adsorption clay deposits. The concentrates from this route contain a larger percentage of heavier rare earths, which require a larger number of separation steps than the light rare earths (Leveque, 2014). Hence, some process-specific differences in energy consumptions and chemical usage can be expected – see Zaimes et al., (2015). According to the impact assessment results from this study, the separation process can amount to two thirds of the overall GWP for separated REO production.

5.7.2 Further research needs in light of the scope of this study

Research needs regarding the life cycle inventory

In order to better understand the additional requirement for precipitants and energy, it would be helpful to conduct further lab experiments to gain insights on the quantitative relationship between ore grades and precipitate consumption. Furthermore, it would be interesting to collect energy consumption data from ore grades of different mines and relate them to production output quantities. Further research is required to understand the fate of emissions from in-situ leaching of REE in the proximity of the mining site, and how these link with different management practices such as wastewater treatment and management of overflow or leakage from pools. To better understand the environmental impacts associated with in-situ leaching, site-specific environmental assessments are recommended.

For the solvent extraction, detailed information on the production routes for individual rare earths was not available. The analysis of the available data has shown that this processing stage is an important contributor to the overall impact and warrants more detailed investigations.

Research needs regarding the quantification of environmental impacts associated with rare earth extraction

Some impacts to the environment could not be sufficiently quantified, either due to missing information required to derive a reliable life cycle inventory, or since they are not addressed by current impact assessment methods. Impacts reported in the literature, but not assessed by current LCIA methods include freshwater salinization, and associated impacts on ecosystems, risks of landslides, and the depletion of minerals (Ca, Mg) in the soil (see (Yanfei et al., 2016; Yang et al., 2013). Stream biodiversity is affected by ammonium sulfate emissions, and the elevated pH (Yang et al., 2013). A detailed fate model for ammonium sulfate emissions was not available, which introduces some uncertainty to the LCI, but the emissions are said to pollute streams in the area long after mine operation is discontinued. Sulfate ions are converted to hydrogen sulphide by microorganisms, which is toxic to aquatic organisms (Yang et al., 2013), citing (Palmer et al., 2010; van der Welle, Marlies E. W. et al., 2008).

In principle, resource depletion is a relevant LCIA category when compiling a dataset for critical metal production. The abiotic resource depletion category in CML (ADP) is not well suited to cover the issues associated with the use of critical metals, as observed by Adibi (2014) and Vahidi (2016). Suitable methods are in development (Sonnemann, 2015). The ADP category in CML relates annually extracted quantities to the overall availability of a specific resource. It thereby only considers one out of three categories of resource criticality as defined by Graedel, namely the supply risks, and only partly considers one aspect considered in this category, namely depletion time – see Graedel et al.(2015). For REEs, the vulnerability to supply risks associated with their unique chemical properties; their importance in green applications, as well as the environmental impacts associated with their production constitute important criticality aspects. Previously lacking ADP characterization factors for REEs are calculated, which draws light to another issue; i.e. the fact that annual extraction rates are not a good measure for resource depletion in case of large supply-demand imbalances, such as in the case of

thulium, holmium, lutetium and ytterbium. Those elements are extracted as by-products, but no large-scale commercial applications exist.

5.7.3 Beyond the scope of this study: Assigning environmental impacts to individual rare earth elements

In some cases, the environmental impacts of individual REE might be of interest. During SX, the rare earths are first separated into groups of rare earths with similar properties which are then further separated into individual rare earth fractions (Chun-Sheng et al., 2016). Hence, the processing routes for the production of individual rare earths are not equally long for each element, and the material and energy requirements could be separated out by element. Ideally, a model would be constructed for each pair of elements which is separated at the last step. The separation of co-occurring elements would only be included in the route to a point where they are partitioned off as groups, in accordance with the production system (Figure 8). For example, to achieve a separation between Pr and Nd, it is necessary to separate the rare earth mix into La/Ce, Pr/Nd and “others”, then La/Ce and Nd/Pr, and then Pr and Nd. However, the separation between Gd, Tb and Dy is not necessary to produce separated Pr and Nd, since they are separated off as a group in an earlier processing step. This procedure would be the preferred option according to ISO 14044, which states that the unit processes should be divided into sub-processes, and the input and output data relevant to these sub-processes should be collected if the environmental impact attributable to the individual process outputs are of interest (DIN EN ISO, 2006a). (It should be noted that this process structure, as shown in Figure 8 is also simplified representation –the sub-processing routes can be crossed in practice – see Yan et al. (2006)). It should be highlighted that this process subdivision is different for different separation systems, which are different for different starting materials - see e.g. (Krishnamurthy and Gupta, 2016; Xie et al., 2014).

Furthermore, the market values of individual rare earths differ notably due to the imbalance between demand and supply for individual rare earths caused by the co-production situation. In order to denote the energy and material requirements associated with the separation process for each individual rare earth element, detailed process information would be required. However, the information on the exact number of processing steps required for each element, and the values of semi-finished products (different rare earth concentrates) are not publicly disclosed.

If the “ideal” solution described here is not feasible, the second best solution (for an attributional LCI dataset) is to apply economic allocation factors to individual elements.

5.7.4 Conclusion

A dataset for the production of rare earth oxides from ion-adsorption clay deposits via in-situ leaching and solvent extraction is provided, based on a previous life cycle assessment study. At the time of writing, a dataset for this route including the separation step had not previously been published. A dataset to represent this route is of interest due to the increasing demand for heavy rare earths such as dysprosium, for which this is currently the most important production route. The dataset presented here includes the separation of rare earth concentrates into individual rare earth oxides, which is essential for many rare earth applications and, as the results show, not negligible in terms of its impact. This study helps further the knowledge about rare earth production from ion-adsorption clay deposits, but also highlights uncertainties associated with the dataset, and points out further research needs, both regarding the life cycle inventory dataset and the impact assessment methods.

Chapter 6 - What difference could recycling make to the environmental impacts associated with rare earth production?

This Chapter addresses the balance problem discussion (Binnemans et al., 2013b; Falconnet, 1985) quantitively in an LCA study. The "balance problem" is a term used to describe the imbalance of demand and supply for some REE inherent to the current production system – see also Section 1.1.3. The reduction of environmental impacts in the global rare earth production system which can be achieved when the demand is partly met from secondary supply is quantified according to scenario estimates for secondary REE supply presented in Chapter 4. A simple model is constructed to quantify the market effects of secondary production. Results show that the impact savings depend on the volumes of Nd-Fe-B scrap available and used for secondary REE production, the process-specific environmental impacts of both the recycling and primary production routes, and on the question to what extent each of the primary production routes can be reduced due to the additional rare earth supply from Nd-Fe-B recycling.

6.1 Introduction

As discussed in Chapter 1, attributional LCA studies have been conducted for both direct and indirect recycling routes, for example Nd-Fe-B material recycling compared to REE extraction from Nd-Fe-B material (Sprecher et al., 2014b; Walachowicz et al., 2014). These studies found the provision of REE from secondary sources through the recycling of Nd-Fe-B magnet material beneficial from an environmental point of view over primary REE production.

The rare earth mix produced from these secondary routes is different to the mix produced through the primary route. This has been discussed as an advantage of secondary rare earth supply, since the supply of rare earth elements extracted from secondary Nd-Fe-B material is closer to the demand mix for REE than the supply mix from the primary routes employed today. The imbalance in demand and supply of the current rare earth production system could therefore be alleviated if recycling played a larger role. In the past this has been predominantly presented as an economic benefit, but there are also potential environmental benefits (Binnemans and Jones, 2015). Elshkaki and Graedel (2014) have highlighted the need to take into account the issue of overproduction when analyzing environmental impacts of REE production.

In attributional LCA studies, process-specific environmental impacts are attributed to the products or services produced from the process considered. In consequential LCA studies, environmental consequences of a decision are modelled by taking market effects into account, and are expressed as the impact of the considered system change ((Zamagni et al., 2012) - see also Chapter 3, for an introduction to the methods used in this thesis, and Section 3.1.2 for an introduction to life cycle assessment). As shown in Chapter 4, the decision to use Nd-Fe-B scrap for secondary REE production could have a significant impact on the market, which is the declared intention of introducing recycling as a mitigation strategy to the balance problem (Binnemans and Jones, 2015). Therefore, the consequential approach to LCA was chosen for this study. The aim of this Chapter is to quantify the global environmental impacts which can be avoided when recycling neodymium, praseodymium, dysprosium and terbium ("magnet REE") from scrap Nd-Fe-B magnet material.

6.2 Methods

Section 6.2 gives an overview of the methods used to answer the research question posed in this Chapter: This study combines findings from Chapter 4 and life cycle inventory data from existing LCA studies to achieve this. Figure 10 shows the steps undertaken for this consequential LCA study. Like

any LCA study, the C-LCA study consists of the definition of the *goal* and scope of the study, followed by a life cycle inventory (LCI) analysis and a life cycle impact assessment (LCIA) phase. At the end, the results are interpreted and discussed. To answer the questions posed in this Chapter, it is relevant whether for “magnet REE” the primary production can actually be avoided to the full extent at which secondary production happens; and whether sufficient supply of all co-products can still be accomplished despite the reduced primary REE output. In LCA studies, the functional unit defines what is being studied, and all results are expressed in relation to the functional unit. For this study, the functional unit and system boundary concern the global rare earth market. They are defined in accordance with the expected effects of introducing a secondary rare earth production system on the market, quantified with the help of the production model.

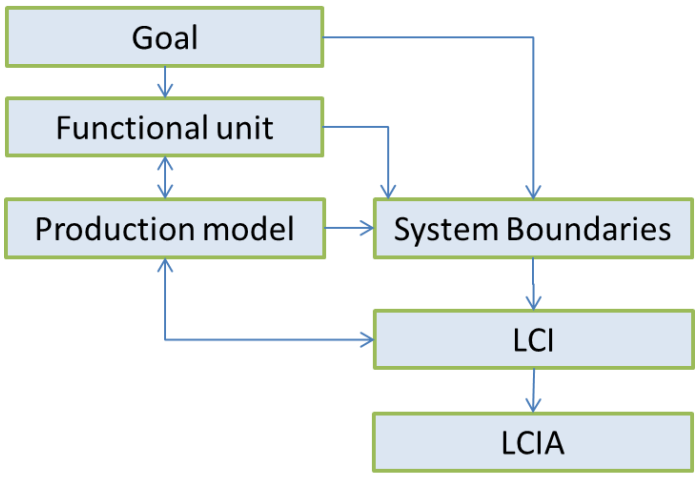

Figure 10: Steps in the C-LCA study

To model the market effects of introducing a secondary production route, data on rare earth supply and demand was necessary. The information on rare earth demand for Nd-Fe-B magnets and REE, and derived potential for the secondary supply were adopted from the MFA study presented in Chapter 4. Since Chapter 4 focused on Nd-Fe-B magnets only, the information was complemented regarding the demand for “magnet REE” for use in other applications from other literature sources (EC, 2014). Due to the joint production of REE, information on the demand trends for other REE was also required. This information was also compiled from the literature (DERA, 2014; EC, 2014) to construct REE demand scenarios for the global REE production. To obtain further information required to model the effects on the market, a basket price calculation was conducted to identify which elements determine the production output for the most common (primary) REE production routes. The insights gained from these calculations were used to construct the production model, which quantitively ‘describes’ the market reactions of introducing a recycling scheme. More details are provided in Section 6.3.

The study is undertaken in order to illustrate the potential environmental benefits of recycling to policy makers and players in the REE recycling industry for an indirect recycling route, and depending on the magnitude of the recycling activities. The question of how to model the avoided primary production of “magnet REE” and their co-products which is addressed by the production model (Section 6.3.3), is important for the definition of the boundaries of the production system to be considered in this LCA study. Since rare earths are traded on a global market, the scope of this study is global. The time period 2020-30 is considered.

For the life cycle inventory compilation, foreground model data for the primary and secondary production systems were taken or compiled from the literature (see 6.5.2. for details), and an indirect recy-

cling route was assumed for all end-of-life magnets. Data for background processes was based on ecoinvent V.3.2 (consequential, long-term model). The modelling was done with OpenLCA 1.4.2. For the life cycle impact assessment, standard impact categories were used (CML baseline).

6.3 Analyzing market effects

Potential market effects of secondary REE production on primary supply are investigated to derive assumptions regarding the extent to which the primary production of LREE and HREE can be avoided when the demand for some elements is met from secondary sources. Two simplified REE production models are constructed; one with primary production only, and one with primary and secondary production.

6.3.1 Key assumptions

- The main primary production route for LREE is from LREE-rich mineral deposits, i.e. bastnaesite, or mixed bastnaesite-monazite deposits which contain small percentages of HREE, and often other metals which are co-mined with the REE. Production from monazite-only deposits has been banned in China due to the high thorium contents in the deposits (Krishnamurthy and Gupta, 2016; Schüler et al., 2011). HREE are mainly mined from ion-adsorption (“ionic”) (alumina-silicate) clay deposits. These deposits also contain LREE. Based on this information, it was assumed that REE production from bastnaesite/monazite in Bayan Obo and from ion adsorption clay deposits constitute the two most important production routes (see also Section 1.1.2). All primary production was modelled as coming from these two main production routes.
- The secondary production of REE from Nd-Fe-B magnets is assumed to be politically incentivized and independent of REE primary production levels. The contribution of secondary sources to the production mix is based on data from the scenario study (Chapter 4). The proposed recycling system produces Nd, Pr, Dy and Tb in proportion to the average content in the magnets.
- Global REE demand has to be met for each individual element in each year.

6.3.2 What determines rare earth primary production output?

Avoiding primary rare earth production – the balance problem

This section addresses the hypothesis that recycling of those rare earths which are highest in demand (Nd and Dy) could help alleviate the balance problem by reducing the demand for those elements and joint REE (Binnemans and Jones, 2015). An alternative and contradicting statement which is found in the literature (Ayres and Peiro, 2013; Nassar et al., 2015b; Nassar et al., 2015a) is addressed in the next paragraph.

Refuting the hypothesis that REE are largely by-products

For ion-adsorption clay deposits, REE are the only products, so the by-product hypothesis is not applicable here. However, for the majority of geological deposits, REE are commonly mined together with other metals, e.g. iron, uranium or titanium (Gupta and Krishnamurthy, 2005). It has been argued that they are mined as by-products of iron ore or other minerals, because they do not generate the main revenue (Ayres and Peiro, 2013; Nassar et al., 2015b; Nassar et al., 2015a). This is being discussed as a cause for supply risks associated with these metals, since it is argued that production quantities are dependent on the production levels for the respective main products. According to Nassar (2015b),

the question of whether a metal will react to market signals (changes in demand/ price) depends on whether it can be profitably mined on its own. This question can be best answered if information on production costs is available.

Due to data limitations, this hypothesis was checked for Bayan Obo only. The revenue contribution of the joint products depends on their respective prices, and quantities sold. The ratio between the iron and REE content varies due to the inhomogeneity of the deposit. The REE content varies between 1 and 6.2% (Gupta and Krishnamurthy, 2005). USGS provide compositional analysis results of some ores in Bayan Obo for a more detailed sub-division of ore types, with up to 25 wt% rare earth oxide (REO) reported (USGS, 1997).

The beneficiation process in Bayan Obo is the processing step which yields REE concentrate and concentrated iron ore at a 1:12.5 ratio (Sprecher et al. ((2014b))[21]. Based on this output ratio, recent prices for iron ore at around 84 $/t (Asian Metal, 2016a) and the value range of REE concentrate at beneficiation stage reported by Kingsnorth (2014b) (around 2-4 $/kg for a 50% REE concentrate), the revenue contribution of iron ore is between 21 and 35%, indicating that REE as a group produced from Bayan Obo deposits are not a by-product of iron ore production. The majority of the revenue from LREE-rich mineral deposits such as Bayan Obo is generated from Nd and Pr. In absence of detailed data for other mines; it was assumed that REE demand does influence production output levels on the global market. This is supported by 1) statements in Asian Metal market reports, which discuss the influence of demand on production outputs (Asian Metal, 2015a), 2) the modelling by Sprecher (2014b) who allocated the majority of the impact from the beneficiation stage to the REE concentrate, based on value allocation; and 3) own discussions with industry experts.

Determining products of LREE-rich mineral deposits

The basket price for LREE-rich ores (i.e. the prices of individual REE metals (oxides) multiplied by a factor representing the average ratio in the ores) was determined, based on average composition data (EC, 2014; Gupta and Krishnamurthy, 2005; Packey, 2016a) and 1- and 3-year average RE metal and oxide prices. Overall, Nd and Pr contribute to around 79% of the basket price, and compositional variation is small. Currently, Sm, La and Ce are produced in oversupply; and it is likely that the marginal revenue contribution originates from Nd and Pr alone. Nd-Fe-B magnets constitute the single most important application driving Nd/Pr demand.

[21] Amongst other elements, niobium is another constituent of the ores in Bayan Obo (Drew et al. (1990)). However, no clear evidence on niobium production from Bayan Obo (or China in general) could be found in the literature and through online searches. Niobium production mainly takes place in Brazil, and, to a lesser extent, Canada (Ronald (2016); USGS (2017b)). Therefore, is was assumed that the production of these elements is most likely only responsible for a minor contibution to the overall revenue at most, and consequently, only iron ore and rare earths were considered in the basket price calculation.

Table 15: Basket price contribution by element for a typical LREE-rich deposit composition, based on prices from Asian Metal (2016), and an average ore composition from Packey (2016a) and Gupta and Krishnamurthy (2005)

	LREE-rich mineral deposits, B. Obo. % REO weight / total REO weight (based on average composition from (Gupta and Krishnamurthy. 2005; Packey. 2016a)	1-year Ø, US $/t REO, Asian Metal 2016, FOB China. 1.11.2014-1.11.2015	3-year Ø, RMB $/t REO Asian Metal 2016, 1.6.2013-1.6.2016	Basket price contribution
Lanthanum	24.0%	3126	17	4-5%
Cerium	50.3%	2761	16	8%
Praseodymium	5.6%	77568	435	26%
Neodymium	17.5%	49954	287	53%
Samarium	1.0%	2795	17	0%
Europium	0.2%	359635	2416	4-5%
Gadolinium	0.7%	11851	109	0-1%
Terbium	0.1%	574150	3041	2%
Dysprosium	0.1%	283170	1566	1%
Holmium. Thulium. Ytterbium Lutetium	0%	30940	0	0%
Erbium	0%	47565	260	0%
Yttrium	0.5%	7935	42	0%
Nd & Pr	23%			79%
Nd. Pr. Dy. Tb	23%			82%

Determining products of ion-adsorption clay deposits (HREE-rich deposits)

Heavy rare earths are mainly mined from ion-adsorption clay deposits (Voßenkaul et al., 2015), which show larger variations in composition than LREE-rich mineral deposits, i.e. bastnaesite or monazite deposits (Voßenkaul et al., 2015; Yang et al., 2013). In order to identify which elements determine the overall production quantities of REE mined from ion-adsorption clay deposits, the contribution of individual REE to the basket price of different reported ore compositions was calculated (EC, 2014; Gupta and Krishnamurthy, 2005; Krishnamurthy and Gupta, 2016; Papangelakis, 2014; Schüler et al., 2011); using 1-and 3-year average prices for individual REO (one- and three-year averages, Asian Metal, 2015b, 2016a). For the purpose of this calculation, it was assumed that the market is cleared for all REE contained in these deposits except for holmium, lutetium, thulium, and ytterbium, for which supply exceeds demand by far (EC, 2014).

Results show that the basket prices for different deposits are dominated either by Dy and Tb, by Nd and Pr, or by a combination of Nd, Pr, Dy and Tb (Table 16). The basket prices are highest for deposits with high Dy/Tb contents. Hence “magnet REE” together determine the basket price for ion-adsorption clay deposits for all analyzed compositions.

Table 16: Basket price contribution by element for different ion-adsorption clay deposits in Southern China, based on prices from Asian Metal (2016), and ore compositions from various literature sources (Gupta and Krishnamurthy, 2005; Packey, 2016a; Papangelakis, 2014; Schüler et al,. 2011)

	1-year Ø, US $/t REO, Asian Metal 2016, FOB China, 1.11.2014-1.11.2015	3-year Ø , RMB $/t RE-OAsian Metal 2016 , 1.6.2013-1.6.2016	wt% REO , ion-adsorp-tion clay deposit , recent Ø pro-duction mix (Pack-ey. 2016a)	Per-centage basket price contri-bution for Packey mix (Pack-ey. 2016a)	wt% REO. Longnan. Ø from different sources (Gupta and Krishna-na-murthy. 2005; Schüler et al., 2011)	% bas-ket price contri-bution Longnan	Wt% REO. Xunwu 1 (Gup-ta and Krishna-na-murthy. 2005)	% bas-ket price contri-bution Xunwu 1	Wt% REO. Xunwu 2 (Schüler et al., 2011)	% bas-ket price contri-bution Xunwu 2	Wt% REO. B1 (Papan-gelakis. 2014)	% bas-ket price contri-bution B1 (Papan-gelakis. 2014)	Wt% REO. B2 (Papan-gelakis. 2014)	% bas-ket price contri-bution B2 (Papan-gelakis. 2014)
Lanthanum	3126	17	28%	2%	1.9%	0%	42%	5%	30%	3%	2%	0%	30%	3%
Cerium	2761	16	3%	0%	1%	0%	2%	0%	7%	1%	2%	0%	6%	0%
Praseodymium	**77568**	**435**	**6%**	**12%**	**1%**	**2%**	**9%**	**25-26%**	**7%**	**17%**	**1%**	**2%**	**6%**	**13%**
Neodymium	**49954**	**287**	**18%**	**24-25%**	**4%**	**5%**	**31%**	**58%**	**30%**	**45%**	**4%**	**4-5%**	**21%**	**30-31%**
Samarium	2795	17	5%	0%	3%	0%	4%	0%	6%	1%	1%	0%	5%	0%
Europium	359635	2416	1%	9-11%	0%	3%	0%	7-8%	1%	5-6%	0%	0%	0%	3-4%
Gadolinium	11851	109	6%	2-3%	5%	2%	3%	1-2%	4%	1-2%	5%	1-2%	4%	1-2%
Terbium	**574150**	**3041**	**1%**	**10-11%**	**1%**	**16%**	**0%**	**0%**	**0%**	**7-8%**	**1%**	**16%**	**1%**	**9-10%**
Dysprosium	**283170**	**1566**	**4%**	**28-29%**	**7%**	**51%**	**0%**	**0%**	**2%**	**15%**	**9%**	**50-53%**	**3%**	**24%**
Holmium. Thulium. Ytterbium Lutetium	30940	0	2%	0-2%	6%	2%	0%	0%	1%	0-1%	9%	0-6%	2%	0-2%
Erbium	47565	260	3%	3%	4%	5%	0%	0%	1%	1%	13%	12-13%	8%	10%
Yttrium	7935	42	25%	5%	66%	13%	8%	2%	10%	2%	52%	9%	14%	3%
Sum			**100%**				**100%**		**100%**		**100%**		**100%**	
Dy & Tb				38-40%		67%		0%		62%		6-7%		43-44%
Nd & Pr				36-37%		7%		83-84%		22-23%		66-69%		33-34%
Nd. Pr. Tb. Dy				74-76%		74%		83-84%		84-85%		72-75%		76-78%

6.3.3 Production model

To construct the production models, the production quantities were linked to Nd and Dy, and the production of the joint REE was assumed to be proportional, in accordance with the respective modelled REE composition of the mined deposit. The production model equations are presented in Annex A3.2.

Demand mix for individual REE

To investigate whether demand is met for all elements for the different production models, a demand mix is constructed for the time period 2020-30 (Table 17).

Table 17: REE demand by individual element, in t REM, low & high Nd-Fe-B demand scenario – own compilation based on Chapter 4 and EC, (2014)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	40.929	43.101	45.319	47.595	49.975	52.486	55.163	57.953	60.875	63.946	67.178
Cerium	57.533	60.534	63.481	66.362	69.395	72.618	76.080	79.639	83.334	87.218	91.298
Praseodymium low	8.941	9.631	10.391	11.224	12.146	13.161	14.279	15.510	16.866	18.359	20.008
Neodymium low	36.024	38.806	41.869	45.226	48.940	53.031	57.535	62.495	67.958	73.975	80.620
Praseodymium high	14.861	17.235	19.865	22.775	25.996	29.570	33.527	37.924	42.820	48.296	54.484
Neodymium high	59.880	69.446	80.041	91.769	104.746	119.146	135.093	152.807	172.536	194.601	219.533
Samarium	1.035	1.143	1.276	1.444	1.623	1.818	2.035	2.284	2.566	2.879	3.228
Europium	350	336	322	309	297	285	273	262	251	241	231
Gadolinium	1.869	2.037	2.220	2.420	2.638	2.875	3.134	3.416	3.724	4.059	4.424
Terbium low	532	542	553	566	579	594	611	629	647	668	689
Dysprosium low	4.020	4.231	4.454	4.687	4.934	5.193	5.465	5.750	6.047	6.358	6.682
Terbium high	665	705	746	785	824	862	898	930	959	984	1.003
Dysprosium high	5.622	6.200	6.775	7.341	7.892	8.425	8.927	9.392	9.809	10.171	10.470
Holmium. Thulium. Ytterbium Lutetium	145	157	170	183	198	214	231	249	269	291	314
Erbium	746	791	838	889	942	998	1.058	1.122	1.189	1.261	1.336
Yttrium	5.525	5.301	5.086	4.879	4.681	4.491	4.308	4.133	3.965	3.804	3.650

Demand for Nd, Pr, Dy and Tb for use in Nd-Fe-B magnets is based on the results presented in Chapter 4. Here, a percentage was added to account for the use of ”magnet REE” in other applications, based on 2012 data (EC, 2014). Two scenarios for REE demand as a function of Nd-Fe-B magnet demand, the single largest market which drives demand for those elements, were compiled (Chapter 4). The scenarios reflect the expected range of future demand for Nd-Fe-B magnets for different Nd-Fe-B applications.

Demand for joint REE is based on EC (2014). For LREE, demand trends are expected to continue beyond 2020. The second most important market for HREE besides Nd-Fe-B magnets is phosphor applications (Schüler et al., 2011). The magnet and phosphor markets recently constituted the sectors in the REE market with highest potential for downstream added value (Machacek and Fold, 2014). Now, due to the increasing adoption of LED lighting with estimates of around 4 to 20% annually (Anonymous, 2016a; DERA, 2014), the market for REE used in phosphor applications is decreasing and the supply situation for REE mainly used in phosphors (terbium, yttrium and europium) is relaxing. (The analysis in Table 16 is supporting this observation). Demand estimates for 2014 are assumed to decline by 4% annually for Eu, Y and the share of Tb used in phosphors, (assumption adopted from DERA (2014)). EC (2014) trends were assumed to continue for years 2020-30 for Er, Gd, Ho, Tm, Lu, Yb (Table 18).

Table 18 - Annual demand growth rates for individual elements (years 2015-30), own compilation from EC (2014), Chapter 4, DERA, (2014)

REE	% growth p.a.
Europium	-4%
Gadolinium	8%
Tb used in phosphors	-4%
Holmium, Thulium, Lutetium, Ytterbium	9%
Erbium	4%
Yttrium	-4%

Production mix under “primary production only” scenario

The production mix was calculated for a situation where REE demand is fully met from primary production. The two main production routes (LREE-rich mineral deposits and ion-adsorption clay deposits) are considered. The REE composition of the ion-adsorption clay deposits varies. The production mix from these deposits was based on the composition reported in Packey (2016) (Table 6), which is representative of ion-adsorption deposit ores currently mined and represents an official Chinese average estimate (Packey, 2016b). The demand was assumed to be met at 100% for both Nd and Dy. The joint products are produced according to the ratios in the respective ores. The numbers show that the demand for Pr and Tb is also met under this condition – see Annex A3 for detailed tables.

In the so-constructed production mix, Dy supply is largely from ion-adsorption clay deposits (Figure 11). The fraction of Nd supply from LREE-rich mineral deposits increases over the time period considered. This is due to the assumed reduction in HREE-content in magnets, which results in a relatively lower increase in production from ion-adsorption clay deposits, especially pronounced for the high Nd-Fe-B demand scenario.

Demand for individual REE is met with the surprising exception of small shortages for cerium in the low Nd-Fe-B demand scenario, in years 2020 and 2021 (7 and 3%, respectively). This can be explained by the large contribution from HREE-rich ion-adsorption clay deposits to the production mix. The deposits are characterized by low cerium contents, due to the formation process (Haschke, 2016). According to

Packey (2016a), around 40% of Chinese REE production was recently provided from illegal mining activities. Ion-adsorption clay deposits contain higher percentages of the valuable HREE and are therefore preferably targeted by illegal miners (Packey, 2016a). Based on these figures, the production mix can be considered a good proxy, even though the percentage of REE production from ion-adsorption clay deposits is lower in recent official estimates (see Lee et al., 2017)

However, cerium production has exceeded demand in recent years and large cerium stockpiles are, and will be available between 2020 and 2030 (Binnemans et al., 2013b; EC, 2014; Matich, 2015). Researchers are trying to find new applications for this low-cost, abundant element – (e.g. (Matich, 2015; Pathak et al., 2015). Due to the large stockpiles, the production figures were not adjusted despite the small cerium shortage.

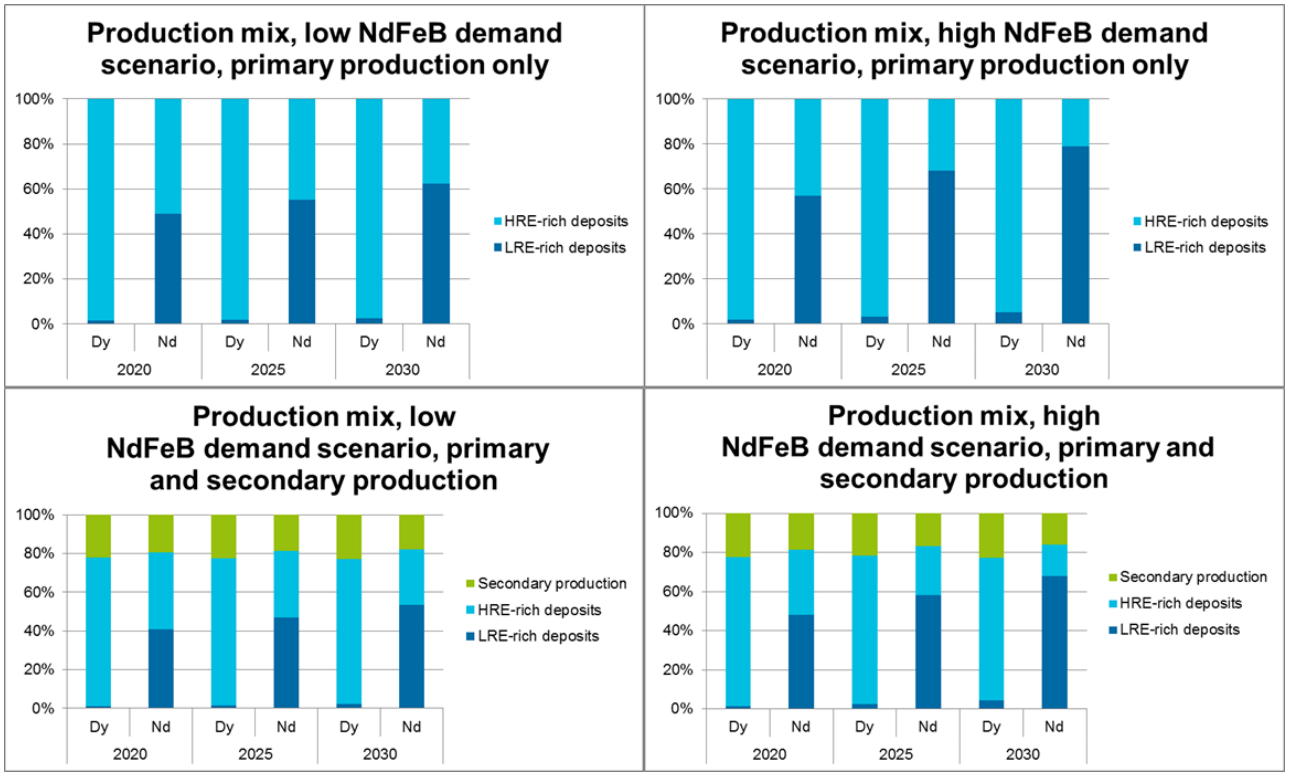

Figure 11: Production mix for Nd and Dy, low and high Nd-Fe-B demand scenario, with /without secondary production

Production mix from primary and secondary sources

When introducing the recycling route to the production mix, an assumption regarding the primary production routes which are being replaced is required. Chinese REE production and processing capacity (around 300 000 tpa) is currently not fully utilized (Kingsnorth, 2014a; Sims, 2014). Nd and Pr mining is mainly from LREE-rich mineral deposits (bastnaesite and monazite), with relatively low variation in Nd and Pr contents (around 15% Nd_2O_3 and 5% Pr_2O_3 in both minerals) (Schüler et al., 2011). Bastnaestite and monazite together account for 97% of minerals contained in global resources (Gupta and Krishnamurthy, 2005). Despite the large stocks of REE ores in countries other than China, these are not currently being widely utilized, since new projects are struggling with economic viability, discouraging new investors (Machacek and Fold, 2014; Paskert, 2014; Schmidt, 2016). Potential hurdles are posed by environmental regulations and the time required to develop new mining projects (Krishnamurthy and Gupta, 2016; Massari, 2013; Moss et al., 2013); making a fast diversification of operating mines unlikely. For these reasons, it was assumed that the current production mix, mainly supplied

from Chinese sources, is a good representation of the marginal primary LREE production mix within the considered time period (2020-30).

HREE-rich ion-adsorption clay deposits show higher variability between sites than other ore types (Gupta and Krishnamurthy, 2005; Nassar et al., 2015a; Talens Peiró and Villalba Méndez, 2013). Therefore, the output mix can be varied by selectively mining individual deposits (Gupta and Krishnamurthy, 2005). This is currently being observed, namely by a shift away from yttrium-rich deposits (Anonymous, 2016a). Ion-adsorption clay deposits contain more of the valuable HREE fractions than other deposits, which makes them attractive for illegal mining, which amounts to ~40% REE production in China, and is often tolerated since production quotas are far below demand levels (Packey, 2016a). The tolerated illegal mining activities, mainly targeted at Nd, Pr and Dy-rich deposits, are crucial for downstream domestic industry since they provide the difference between legal supply and demand for REE (Packey, 2016a). Operators do not pay mining license fees; often do not adhere to environmental standards, and selectively focus on high-grade deposits, thereby lowering their own production costs and reducing the economic viability of the remaining degraded deposit (Packey, 2016a). The processing costs per unit of output increase with decreasing ore grades, since larger inputs of chemicals and energy are required – (see Krishnamurthy and Gupta, 2016; also Calvo et al., 2016). The mining of leaner ores is also associated with higher environmental impacts (Krishnamurthy and Gupta, 2016).

Due to the variability of the deposits and the illegal mining activities, the marginal composition is difficult to determine. The production mix from these deposits was based on the composition reported in Packey (2016) (Table 6) (see previous section), which is representative of ion-adsorption deposit ores currently mined.

The production mix was calculated for a situation where the potential for secondary REE production for “magnet REE” is realized according to scenario estimates detailed in Chapter 4. Thus, a third production route is added to the supply mix, and the model expanded to cover supply from secondary sources, and reduce the two primary production routes so that supply meets demand for Dy and Nd each year. Other REE are produced, as per the compositions in the ores. The calculation is detailed in Annex A3. With the introduction of the secondary REE production route, demand is still met for individual elements, with the exception of cerium for years 2020-24 for the low Nd-Fe-B demand scenario (23% short in 2020, decreasing to 4% in 2024, with sufficient supply from 2025) (see Table 39 and Table 41). As for the primary production scenario, the production output was not adjusted upwards; due to the large stockpiles reported in the literature.

Again, the production from LREE-rich production route only contributes a small amount to the overall Dy supply (Figure 11). Secondary production reduces the primary production output, and therefore the overproduction. However, since the overall REE demand is increasing, there is still an increasing overproduction, even if primary production is partly replaced by secondary production (Figure 12).

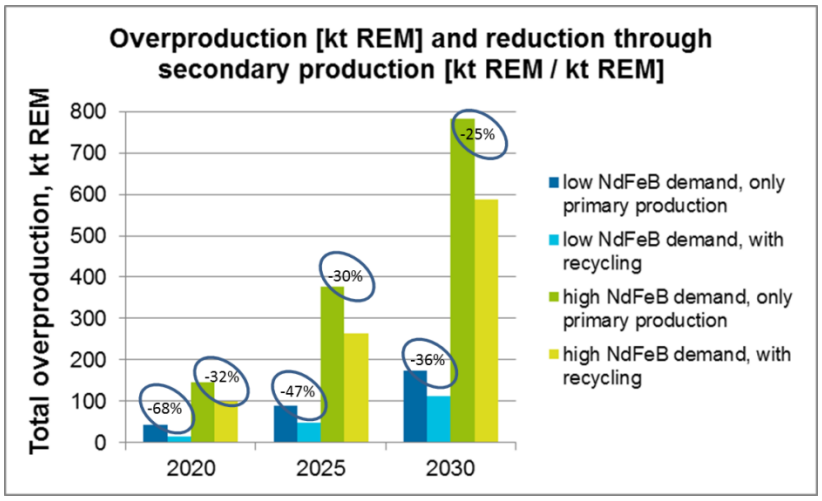

Figure 12: Overproduction (production minus demand for sum of REE in kt of metal weights), and percentage reduction achievable by secondary supply, by year and scenario

6.4 Functional unit

The functional unit comprises the global production of REE to meet the demand for individual lanthanide elements from lanthanum to lutetium plus yttrium, excluding promethium, at >99% purity of the oxides. The future demand volumes act as the quantitative reference units for which potential environmental impact savings are reported. Due to the scenario approach, the size of the reference flows, expressed in metal volumes demanded, differs by year and scenario (Table 19 and Table 20). The production levels are identified by means of the production model. The analysis shows that if demand is met for Nd and Dy, this automatically implies that demand is also met for Pr and Tb (Annex A3). Although Nd and Pr, and Dy and Tb, are exchangeable to an extent in Nd-Fe-B magnet material, the elements show differences in price and application: therefore, they were treated as four individual elements in this model.

The demand can be met by supply from primary production only, or by a combination of primary and secondary production. The difference in environmental impacts between the two systems was analyzed. Since the difference is reported for a future production system, the overall savings are a function of the future demand volumes. Results from Chapter 4 were used as estimates. Results are presented for a low and a high Nd-Fe-B demand scenario, which results in different demands for the REE used in Nd-Fe-B magnets (Nd, Pr, Dy, Tb).

Table 19: Size of functional unit, global REE demand by element, low Nd-Fe-B demand scenario, years 2020; 25 and 30 in t of metal weights, compiled from Chapter 4 and (EC 2014)

	Nd	Pr	La	Ce	Sm	Er	Y	Eu	Tb	Gd	Ho, Tm, Yb, Lu	Dy
2020	36020	8940	40930	57530	1030	746	5525	350	532	1869	145	4018
2025	53030	13160	52490	72620	1820	888	4491	285	594	3314	214	5191
2030	80620	20010	67180	91300	3230	1056	3650	231	689	4424	314	6679

Table 20: Size of functional unit, global REE demand by element, high Nd-Fe-B demand scenario, years 2020; 25 and 30 in t of metal weights, compiled from Chapter 4 and (EC 2014)

	Nd	Pr	La	Ce	Sm	Er	Y	Eu	Tb	Gd	Ho. Tm. Yb. Lu	Dy
2020	59880	14860	40930	57530	1030	746	5525	350	665	1869	145	5627
2025	119150	29570	52490	72620	1820	888	4491	285	862	3314	214	8430
2030	219530	54480	67180	91300	3230	1056	3650	231	1003	4424	314	10474

6.5 Production routes, system boundaries and life cycle inventory analysis

6.5.1 System boundaries and production routes studied

The analyzed system covers the two main primary production systems from LREE-and HREE-rich (ion-adsorption clay) deposits from ore to REO production (through solvent extraction), and the recycling process as an alternative route, covering the extraction of EOL magnets from a compound (e.g. motor), demagnetization, chemical dissolution of the magnet in acid, separation of REE from non-REE metal content, and separation of individual REE by solvent extraction (Figure 13). The reduction from RE oxide to RE metal was assumed to follow the same process (molten salt electrolysis), regardless of

whether the REO originate from primary or secondary sources. Therefore, this step was omitted from the comparison. Note that the functional unit is nevertheless expressed in metal quantities, the chemical form required for use in alloy production.

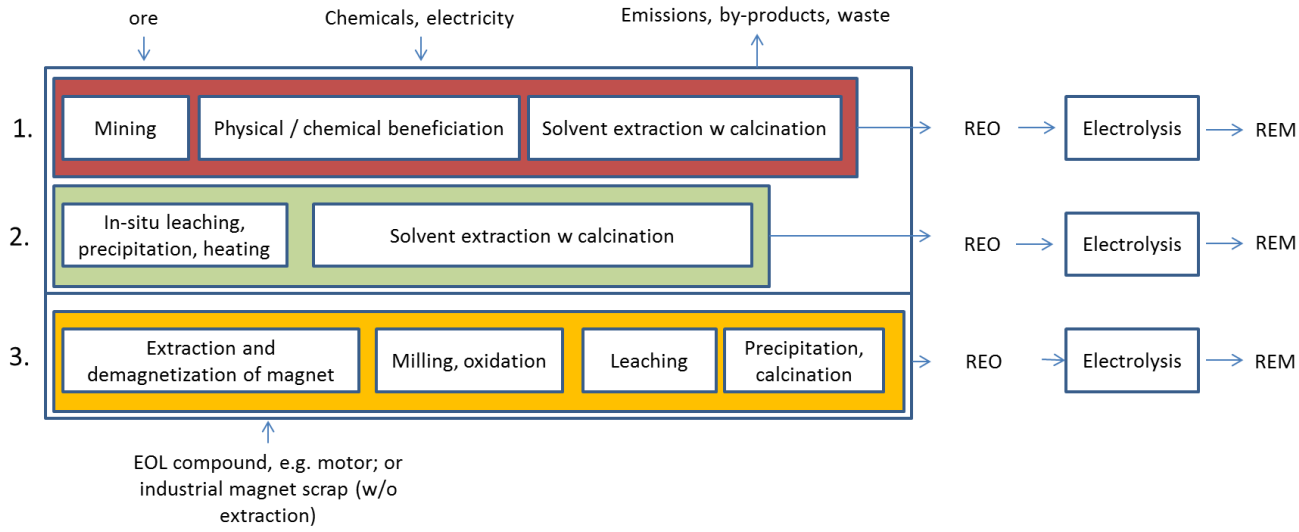

Figure 13: System boundaries of the two product systems for the three REE production routes: REE production from 1) mineral, LREE-rich mineral deposits, 2) from ionic, HREE-rich (ion-adsorption clay) deposits, and 3) from secondary production (extraction from Nd-Fe-B scrap)

6.5.2 Life cycle inventory analysis

Foreground life cycle inventory (LCI) data, i.e. the quantitative information on material and energy requirements, waste and emissions for the primary production routes, was based on the production from LREE-rich mineral deposits from Bayan Obo in Inner Mongolia, China, the largest rare earth mine, and production from HREE-rich deposits from ion-adsorption clays (Sprecher et al., 2014b)[22]. Foreground LCI data from the MoRe (Motor Recycling) project[23] was used to represent the recycling route – see Bast et al (2015) Walachowicz et al. (2014) for a description of the process (IFAD route 3).

The recycling process dataset was adjusted to represent quantities of individual REE obtainable, based on the scrap compositions from Chapter 4, which slightly differ by year and scenario. The material and energy consumption of the recycling process was adopted from the literature (Walachowicz et al., 2014).The dataset used to model REE production from LREE-rich mineral deposits compiled by Sprecher et al. (2014b) was adjusted to include the elementary flows and output ratios for individual REE to match the composition used for the production mix modelled in this study.

For all LCIs, the underlying background datasets were exchanged for “ecoinvent, consequential, long-term” datasets to represent a consequential system model. The primary production processes were assumed to happen in China, where the majority of REE production currently happens and overcapacities exist for REE processing. For electricity used directly in the primary or secondary REE production processes, datasets were adjusted for better geographical and temporal representativeness (detailed in Annex A3).

[22] The compilation of the dataset is addressed in a separate publication, since it is not essential for the storyline of this paper.

[23] The MoRE (Motor Recycling) project was a research project on the recycling of components and strategic metals from drive motors (https://www.siemens.com/press/en/presspicture/?press=/en/presspicture/innovationnews/2011/in20111202-01.htm).

6.6 Results

Impact assessment results are presented for selected impact categories. The characterization factors for “ADP elements” were adjusted for REE according to the calculation rules for this method. Details are described in Chapter 5 (5.6.3).

Results show that the impact of the recycling process is lower than the impact of the alternative primary production processes which could be replaced by the secondary supply. Hence, partly replacing primary REE production with production from secondary REE, obtained through recycling of Nd-Fe-B scrap, could reduce the overall impact of the global REE production system. Whilst the same general trend is observable for all presented categories, differences between impact categories can be observed. For example, the production from HREE-rich (ion-adsorption clay) deposits is characterized by a large eutrophication potential, although with large uncertainties.

The results are a function of process-specific impacts per metric ton of REE metal received from each production route (Figure 16), REE quantities available for recycling (A3 - Figure 1) (which determine the size of the system change), and the percentages of determining products in each mix, which impact the total quantity of REE that need to be extracted to obtain the required quantities of the determining products (Figure 15). The net avoided impact per metric ton of recycled REM decreases over time (Figure 17) since the fraction of the avoided REE production from HREE-rich (ion-adsorption clay) deposits, which has a higher specific impact, is decreasing (see also Figure 11).

The total avoided primary REE metal production from different routes is illustrated in A3 - Figure 2. This is a result of assumptions taken for the production model (Section 6.3.3) as well as the overall possible extent of secondary REE production.

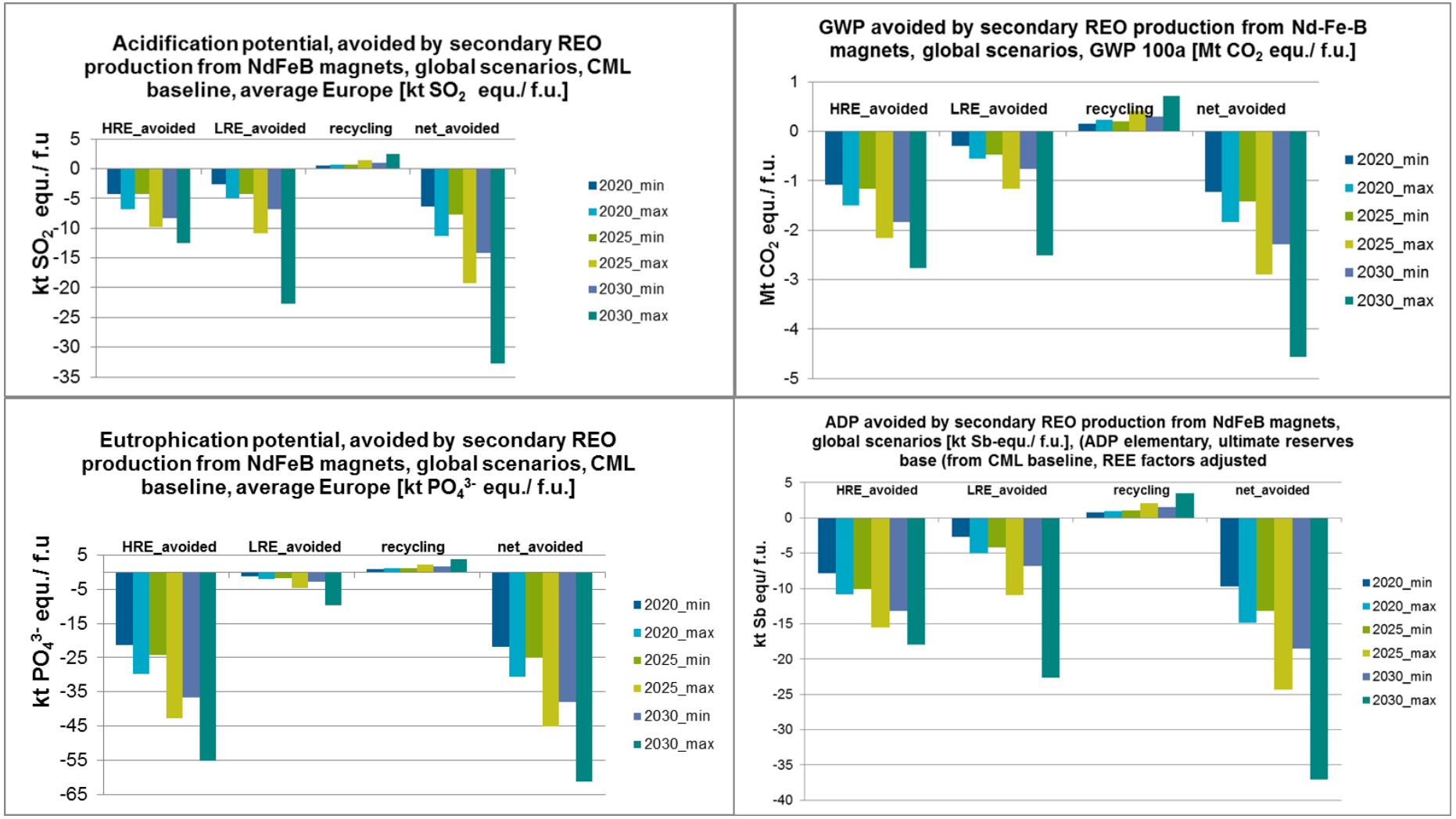

Figure 14: LCIA results for selected impact categories and different Nd-Fe-B demand scenarios – the "min." and "max" values here refer to the low and high Nd-Fe-B demand scenarios in Chapter 4)

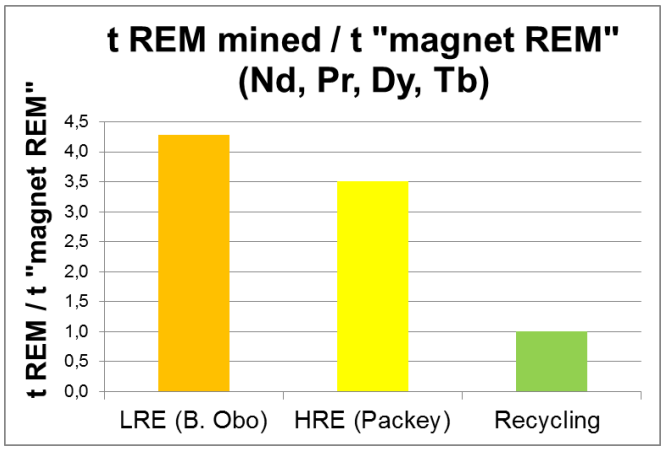

Figure 15: t REE mined/t "magnet REE" (sum of Nd, Pr, Dy, Tb) from different deposits in t REM (metal weights)

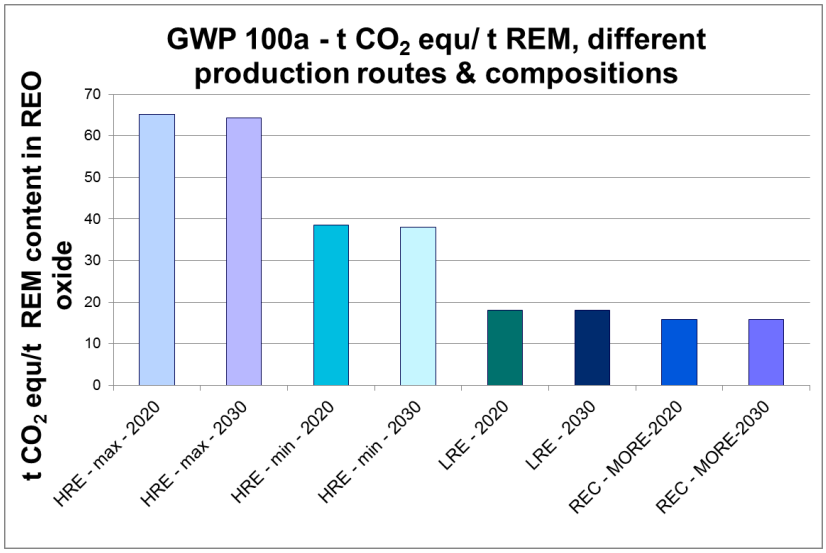

Figure 16: Process-specific GWP 100a impacts per metric ton of REE metal (in t REM), (impact per t of REM content of the different production routes shown in Figure 13, different compositions, displacement of recycling not included)

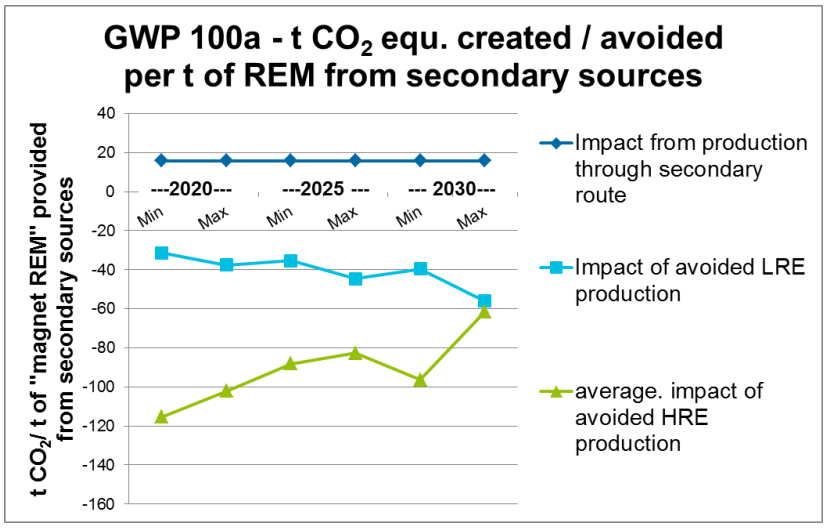

Figure 17: and CO_2 equ. / avoided per t REM provided from secondary sources (results normalized to 1 metric ton of secondary REM)

6.7 Discussion and conclusion

In this chapter, the effects of REE recycling from Nd-Fe-B magnet material on the global environmental impacts from REE production were analyzed for the potential secondary REE production estimated in a previous MFA study (Chapter 4). The recycling activities were assumed to be politically incentivized and to happen according to scenario estimates from Chapter 4, according to which around 20% of the demand for “magnet REE” could be provided from secondary sources.

Producing some of the REE which are highest in demand and determine the overall production quantities in the current primary production system has been suggested as a means to reduce the primary production output and overproduction (Binnemans and Jones, 2015). This hypothesis was tested by describing the market situation with the help of a simple production model to test which effects on the environmental impacts are likely to be expected. The production model specifies how much production is avoided from each of the two main production routes. It was shown that “magnet REE” Nd, Pr, Dy and Tb determine production output levels for all analyzed deposits, and that a production mix which combines primary and secondary REE production still provides sufficient quantities of all individual REEs.

Due to the joint production situation, reducing the primary production is generally only possible for all joint products as a whole, due to the joint occurrence of REE in the ores. This is true for most processing stages in the REE supply chain, whose output is a mix of REE. Hence, replacing some of the primary production mix by secondary production does have an impact on joint REE, and the system needs to be expanded to take this into account. There are some exceptions: in solvent extraction the last separation stages between individual REE can be omitted and semi-finished products temporarily stored, if supply exceeds demand for selected output groups. However, LCI data was not available at this level of detail. Therefore, the avoided primary production process was modelled as a unit and not subdivided any further.

Results show that the avoided impact from primary production far exceeds the impact from the recycling activity for all analyzed impact categories. Uncertainties associated with the REE quantities available for recycling, foreground and background datasets do not impact the overall finding. The findings are in line with those of previously conducted attributional LCA studies in terms of the conclusion that REE recycling from Nd-Fe-B is environmentally beneficial over primary production (Sprecher et al., 2014b; Walachowicz et al., 2014). However, this study shows that this is not only a result of the differences in process-specific impact of the recycling and primary production processes, but also a consequence of the market effects.

There are reasons why the real production situation is more complex than the model. The provision of the determining elements of the primary production through secondary sources avoids both their primary production *and* the co-products of primary production, since no demand shortages are to be expected for these by-products even with maximum recycling, with the surprising exception of small cerium shortages, for which plenty of stockpiles are available. It was assumed that this overproduction would not be missing on the market and therefore not be produced elsewhere. This is a simplification, since there may be value in storing co-products for future use. The market might be cleared over longer time periods, e.g. as a result of a new material developed, or a technology shift (e.g. researchers are working on the use of Ce instead of Nd in permanent magnets (Pathak et al., 2015). The production model presented here does not address such a technology shift.

If REE from secondary Nd-Fe-B sources were available in such quantities that a reduction in primary production could be expected to cause shortages for some joint REE, the price for those joint REE would increase, and they might then become determining products in their own right. Then, the basket

price calculations would also no longer be valid. Hence, it should be highlighted that the results are applicable in the specific context of this study, including the time frame and scenario assumptions.

The assumption that the global production output should meet demand for each element in each year is a simplification. Divergences from this balanced situation can be managed by stockpiling of finished and semi-finished products. This has not been quantitatively addressed by this model, but has been qualitatively taken into account for cerium, where it was assumed that stockpiles available due to the current oversupply could be used to balance the demand-supply situation in the future.

Furthermore, with the growing REE demand, the primary production mix which is likely to be avoided on the global market by recycling of Nd-Fe-B magnets depends on various political, economic and other factors, including the geological variability of the HREE-rich (ion-adsorption clay) deposits, state regulation of the REE market in China, and the perceived geopolitical supply risks, which affect market decisions outside China. These factors all affect the overall environmental impact which can be avoided when some of the primary production is replaced by a secondary production route. Whilst they could change the magnitude of the avoided impact, only a radical technology change with implications on the determining REE for each production system and/or the process-specific LCIs would clearly challenge the results.

Chapter 7- Process-specific impacts of other recycling technologies: a one-step recycling process for REE extraction from Nd-Fe-B magnets using molten salt electrolysis

Chapter 6 presented an estimate for the possible reduction of environmental impacts in the global rare earth production system through the introduction of a recycling system for rare earths from magnet materials, considering market effects, and a specific recycling process technology. REE recycling from Nd-Fe-B magnets is expected to play an increasingly important role in future REE supply (Yang et al., 2016). However, no larger-scale, commercial recycling operation for rare earths from Nd-Fe-B magnets exists to date; and it is still open which recycling process technology would most likely be applied on an industrial scale. Different recycling processes are being developed in EREAN and other projects (Section 1.3), with different process-specific impacts. This Chapter presents an initial life cycle assessment study for one of these alternative recycling processes, which uses molten salt electrolysis to extract REE from magnet scrap. The results should be interpreted as an early estimate that can serve as a basis for further investigations.

7.1 Introduction

This Chapter presents a life cycle assessment study of an alternative recycling process during which REE are extracted from scrap magnets through molten salt electrolysis. The goal of this study was to identify the process-specific impacts associated with this route and to compare them against those of the most common primary production route for rare earths. The influences of important processing choices which affect the environmental impacts of the process being developed are discussed. REE are required in metallic form for Nd-Fe-B magnet production. Direct (magnet material recycling) and indirect recycling routes are being developed to recycle the magnet material as a whole or extract the rare earth elements, respectively (Binnemans et al., 2013a). Direct recycling processes can be expected to be most environmentally advantageous due to the short processing routes, only surpassed by magnet reuse (see Walachowicz et al., (2014)). Indirect metallurgical recycling methods offer more flexibility in that they are less sensitive to contamination and variability of the input material stream. They can produce individual elements as outputs, but typically involve numerous processing steps in which the rare earths are separated from exogens (iron, boron and impurities), and individually separated and reduced from rare earth oxides to metals – see e.g. (Bast et al., 2015; Binnemans et al., 2013a; Önal et al., 2015).

A new recycling process is being developed that is based on the direct extraction of rare earths from EOL magnet material in a molten salt electrolysis bath, thereby omitting the need to conduct a more complex, multi-stage process. This new process development is technologically challenging, but a single-step recovery of REE from magnetic scrap is very attractive from an industrial implication point of view (Borges de Lima, Ismar and Filho, 2016). Hence, various research groups are working on this topic – see e.g. EREAN, 2015; Hua et al., 2014; Ryu et al., 2015. Extraction processes are promising in that they are generally suited to handle Nd-Fe-B scrap with variable compositions and contamination levels (Firdaus, 2016 citing Takeda et al., 2014). Furthermore, since the electrolyte is reusable and the processing chain is short, the one-step recycling process is expected to be environmentally beneficial when compared to longer processing routes (see Borges de Lima, Ismar and Filho, 2016; Takeda et al., 2014). Conducting life cycle assessment to support R&D can help steer process development into an environmentally favourable direction (Miller and Keoleian, 2015). To date, no life cycle assessment studies have been conducted for this new process. Here, an LCA study was conducted to provide a quantitative estimate of the impacts associated with the process being developed. The results can help guide process development from an environmental impact point of view.

7.2 Process description

The one-step recycling process for the extraction of rare earth metals from scrap magnets is being developed on laboratory and pilot scale at TU Delft. For the lab-scale experiment, non-magnetized, uncoated magnet samples were used. The magnets were ball-milled to increase the surface area to facilitate the electrochemical reactions, and the powder was inserted into the salt bath. The following electrolysis constitutes the most technologically challenging process step, and is the focus of the research undertaken at TU Delft.

The experimental setup consists of an electrolytic cell with lithium fluoride used as an electrolyte. Aqueous solutions are unsuitable since rare earths would react with water and oxygen (Borges de Lima, Ismar and Filho, 2016).

The cell is positioned within a resistance furnace used to heat the bath to obtain molten lithium fluorides (LiF). An iron anode and a molybdenum cathode are used. The milled magnet powder from which the REE are to be extracted is added to the electrolyte. The process temperature (~950°C) is maintained throughout the process, which is conducted under a protective argon atmosphere to prevent oxidation of the extracted REEs.

Neodymium fluoride (NdF_3) is added to the mixture as catalyst to initiate the electrolysis process. Current (from a different circuit to the one heating the resistance furnace) is applied to start the electrochemical reactions, which first decomposes the NdF_3 (Equation 1) since it is less stable than LiF. Nd^{3+} is reduced on the cathode and F_2 ions are oxidized at the anode hence FeF_3 is formed on the anode (equations 2 and 3). The anode is consumed in this process.

$REF_3 \rightarrow RE^{3+} + 3F^-$ For RE=Nd E=-4.7 V at T=950 °C [Equ. 1]

$RE \rightarrow RE^{3+} + 3e^-$ [Equ. 2 cathodic reaction]

$Fe + 3F^- \rightarrow FeF_3$ [Equ. 3 anodic reaction]

FeF_3 then reacts with the REE contained in the molten magnet material and the REE in the magnet material is exchanged for Fe from the FeF_3 to form REF_3, thereby extracting and separating the rare earths from the iron and boron (Equation 4).The fluorite ions are thereby liberated and move to the anode, which maintains the reaction. The additional Fe in the magnet material takes the form of an intermetallic phase, such as Fe_2B or FeCo (not shown).

$RE(magnet) + FeF_3 (salt) \rightarrow REF_3 (salt) + Fe$ $(magnet)\Delta G^o [950^oC] = -588KJ$ [Equ. 4]

The cell voltage causes the REF_3 to dissociate (again - Equation 1). The rare earths are reduced at the cathode and are deposited in layers of different REE, with the (electrochemically) favoured reaction happening first (Equation 2).

A variation of the process uses the scrap magnet directly, i.e. the magnet material is not milled prior to the electrolysis, but inserted directly into the electrolysis bath in lieu of the iron anode. Hence, the scrap magnet is then anodically dissolved and reacts with FeF_3 which is added directly into the bath as fluorinating agent. As a result of this reaction, NdF_3 is formed, which will subsequently dissociate again (Equation 1).

An unintended side reaction may occur in both process variants if the FeF_3 is decomposed before it reacts with the scrap magnet material. In this case, the Fe would be deposited at the cathode and the fluoride ions would maintain the anodic reaction.

7.3 Experimental set-up

For the experiment, lithium fluoride (98.5%-Alfa Aesar) was mixed in a glove box with the Nd-Fe-B magnets (supplied by Magneti Ljubljana), previously ball-milled into fine powder. The magnet composition as provided by Magneti Ljubljana is shown in Table 21. 15g of milled magnet powder were processed in one experiment. Neodymium fluoride (99.9%-Alfa Aesar) was added in order to initiate the electrolysis process. This mixture was then charged into a graphite crucible[24] and heated up to 950°C for 3 hours under argon atmosphere, with an applied current of 20A for the resistance furnace, and 15A for the processing current driving the electrolysis.

Table 21 Composition of the neodymium magnet supplied by Magneti Ljubljana analysed with XRF (x-ray-fluorescence).

Element	Nd	Dy	Al	Fe	B	Co	Pr	Cu	Ga	Total
Wt. %	28.9	2.72	0.14	63.4	-	2.91	0.67	0.19	0.07	99.0

After completion of the electrolysis, the samples were analysed by X-Ray Diffraction (XRD) as well as by Electron Probe Micro Analysis (EPMA) in order to determine the phases that are formed during the experiments and their compositions. The conversion of the neodymium in the magnet into neodymium fluoride was earlier proved in the same lab (Abbasalizadeh et al., 2017). The results from XRD and EPMA show the deposition of neodymium and dysprosium on the molybdenum cathode.

The experiments showed that the reaction between the magnet material and FeF_3 (Equ. 4) works with a very good efficiency in a lab setting.

Furthermore, it could be shown that neodymium and dysprosium can be extracted from the magnet material, i.e. a REE mischmetal product can be produced at the cathode, which corresponds to the composition of the REE in the magnet. The REE are deposited in metal form and individually in layers. The process development is challenging due to the high reactivity of rare earths at high temperatures: Despite the protective atmosphere, the REE are currently oxidized at the cathode. So far, it could be shown that the process is feasible in principle. Further experiments are required to determine the recovery yield in lab- and pilot scale environments. Furthermore, the degree to which unintended side reactions occur remains to be tested.

7.4 Methods

An attributional life cycle assessment study was conducted in accordance with the goal and scope definition (Section 7.5). For the life cycle inventory compilation, qualitative information on the process was obtained in close collaboration with the researcher developing the process. Since at the time of writing, the process development so far had focussed mainly on the proof of principle, but had not yet been implemented on an industrial scale, assumptions were required to compile the foreground data (i.e. data on process-specific material- and energy consumption, waste and emissions). They were based on relevant literature regarding primary rare earth production and aluminium production, and discussions with experts from the group developing the process. To account for uncertainties associated with the life cycle inventory data, and the associated process-specific impacts of the foreground process, a range of values is presented in the life cycle inventory.

[24] Fluoride is very corrosive, thereby limiting the options for materials which can be used for the crucible. On an industrial scale, graphite crucibles are commonly used. For research purposes, inert metals such as Mo, Ni, Pt and W can be used.

The modelling was done in OpenLCA (Version 1.4.2). Ecoinvent V.2 (apos_2) data was used to model the background processes[25]. A standard set of impact assessment methods (CML baseline, Version 4.4. of January 2015) was used for the assessment.

7.5 Goal of the study, considered scope and system boundaries

The aim of this study was to conduct a (gate-to-gate) life cycle assessment study in order to determine the potential impact of the one-step recycling process of REE from scrap Nd-Fe-B magnets through molten-salt electrolysis. The environmental impacts from this process route can also be compared against impacts from alternative primary production processes for REE. Furthermore, process developers can be informed about the potential impacts of the process being developed, and about the aspects that should be given special attention from the point of view of reducing overall process impacts. Since the recycling process is at an early stage of development, the analysis cannot present an exact figure. Rather, the influence of different factors can be tested.

The functional unit of this analysis is the production of one kg Nd/Pr alloy through extraction from Nd-Fe-B magnet scrap[26]. The boundaries of the analysed system include the molten-salt electrolysis recycling process, which includes the extraction of the magnet from its compound (e.g. a motor) demagnetizing, decoating and ball-milling of the magnet, followed by the electrolysis step. The product is an REM alloy with approximately the composition of the REE in the original magnet, at purity levels sufficient for use in magnet production. The first life of the magnets, collection and transport of end-of-life magnet applications to the recycler are not included in the analysis.

The extraction of the magnets from EOL compounds, demagnetizing and cleaning steps were not conducted in the lab, but would be required if the process was implemented in practice. They are therefore included in the life cycle inventory. The focus of this study is on the electrolysis process since it is the most technologically challenging processing step, and the focus of research efforts of the researcher developing the process. Data is compiled from literature and complemented with expert discussions held with the researchers developing the process, and data provided by a magnet manufacturer.

The production, use, collection and transport phases of the Nd-Fe-B appliances are not included in the analysis.

[25] Background processes are processes not directly related to the recycling process itsself, such as the production of chemicals and electricity used in the process.

[26] For this LCA study, the focus was on the assessment of recovering Nd and Pr, which make up the bulk of the REE fraction. Including a possible recovery of Dy from magnet scrap in a comparative LCA study would further enhance the environmental benefits of the recycling process (if the LCA studies used for the comparison apply economic allocation).

Figure 18: Processing steps for the EOL-magnet recycling process – two process variants, with and without milling

7.6 Life cycle inventory - recycling process – assumptions

7.6.1 Expected (qualitative) differences between lab- and industrial-scale setup

When using EOL magnets as input material for the electrolysis, the magnets need to be extracted from their compounds (e.g. motors), demagnetized, cleaned and milled.

Contrary to the laboratory setup, which uses a resistance furnace to obtain the required temperature of the salt bath and a power source to drive the electrolysis, in an industrial setup, the heating and the current would both be supplied from the same power source (Lucas et al., 2015; Yang, 2016). The process being developed closely resembles the Chinese state-of-the art molten fluoride electrolysis process for rare earth reduction (see Vogel et al., 2015). The current is fixed and maintained at a certain level. Current efficiency, defined as the percentage of the cell current utilized to deposit the target metals at the cathode, effectively varies over time. Amongst other factors, this depends on the extent to which side- or back-reactions happen, impurities are deposited and short circuits occur (Yang, 2012). Since the same current drives both the heating and the electrolysis process, some slight temperature variation is to be expected. The cell resistance may increase during the operation, e.g. due to an increase in impurities in the cell.

In the previously conducted lab-scale experiments, the focus has been on proving process feasibility, rather than optimizing energy and material utilization. For this reason, the electrolyte has been exchanged for each experiment conducted. If the process was implemented on an industrial scale, the electrolyte would be reused (Borges de Lima, Ismar and Filho, 2016). The infrastructure, including the electrodes, electrolyte and the bricks which are part of the cell construct, is replaced every 5 months (Vogel et al., 2015).

It was assumed that the typical Chinese 3kA technology is representative of the technology size of the equipment which would be used for the Nd-Fe-B recycling process when implemented on an industrial scale[27]. The process developed at TU Delft can be conducted at a slightly lower temperature than the industrial scale reduction of REO to REM. It has been mentioned in the literature that the process temperature is a factor considered in optimization efforts for the industry process (Zhang et al., 2013). However, since the differences in temperature are expected to be small, the industrial setup is assumed to be a representative estimate for the purpose of this study.

[27] Although larger cells have been developed, the data given in the literature is for the 3kA cells which are said to be the most common technology still.

7.6.2 Extraction of the magnet from the compound, demagnetizing and decoating

The life cycle inventory data for the extraction of the magnet from the compound, demagnetizing and decoating is based on a previously conducted life cycle assessment study (Walachowicz et al., 2014). The magnets are separated from the permanent magnet motors with the help of pressurized air; demagnetized with infrared light, and cleaned /polished with silicon carbide and reusable polyphenylene sulfide granule (Walachowicz et al., 2014). A detailed description of the processing steps analysed in this study can be found in Bast et al. (2015) and Walachowicz et al. (2014). The data (presented in Table 22), based on the extraction of magnets from traction motors used in electric cars, is used here as a proxy for different end-of-life Nd-Fe-B applications. It should be noted that the losses of magnet material during the extraction from its compound could, in practice, differ between EOL-Nd-Fe-B applications. The effective removal of the magnets will, in practice, depend on the development of suitable dismantling and/or extraction processes. Successful trials have been undertaken for some applications, which, besides traction motors, include hard disk drives and air compressor motors (Hitachi Ltd., 2010; Mitsubishi Electric, 2014b).

7.6.3 Ball-milling of magnet material (Process variant 1 only)

After cleaning, the material is milled under a protective argon atmosphere to prevent oxidation. The milling step is undertaken to increase the surface area to facilitate the rare earth extraction. The energy consumption of the ball-milling step can be estimated from the hardness of the material being milled, and the particle sizes before and after the milling (Tsakalakis and Stamboltzis, 2004a; Tsakalakis and Stamboltzis, 2004b). (The data is included in Table 22, but only relevant to the process variant with milling). The grain size produced in the lab experiment is ~200 µm.

7.6.4 Electrolysis

Magnet composition

The magnets can vary with regards to their content of individual rare earths. Usually, Nd, Pr, Dy and Tb, sometimes Gd are present in Nd-Fe-B magnets. Since the REE have very similar electrochemical properties and therefore show similar behaviour in the process, no distinction is made for magnets with different REE compositions for the purpose of this analysis.

Process yield

With the current state of the lab experiments, detailed information on process yields for the reduction step, i.e. the fraction of the rare earth material contained in the magnet material which can be harvested as rare earth metal deposited at the cathode is not yet available since the focus of the research has so far been on the proof of principle. Hence, it is also not yet known to what extent the milling of the magnet material improves the yield. Therefore, a wide range of 50 % to 95 % was modelled. The 95 % corresponds to the best yield reported in the literature for primary REM production; the 50 % represent a conservative estimate.

Energy consumption

In rare earth primary production, reducing rare earth oxides to metal is the processing stage which consumes most process energy per kg REM (Talens Peiró and Villalba Méndez, 2013), and research is being undertaken to improve the current efficiency for rare earth electrowinning processes with alkali halides (Yamamura et al., 2004). Energy is required to both drive the extraction via a direct current *and*

maintain the temperature at which the reaction takes place (around 950°C). For this study, the energy consumption was assumed to be continuous throughout the lifetime of the electrolytic cell (150 days).

The theoretical electricity consumption required for the deposition current can be calculated using Faraday's law (Talens Peiró and Villalba Méndez, 2013; Yang, 2012). According to this law, for each type of metal, the (theoretical) amount which is deposited can be calculated for a given plating time and amperage. In practice, losses occur due to side reactions etc. A current efficiency factor of 65-78 % is representative of the industrial fluoride system (Gunawan, 2015 citing Zhu, 2014). The power consumption for the DC current driving the reaction is around 9-13 kWh/kg rare earth metal, with a REM material yield of 90-95% (Siming et al., 2011; Talens Peiró and Villalba Méndez, 2013; Vogel et al., 2015). According to Talens Peiró and Villalba Méndez (2013), the energy requirement is on the higher end of this range for mischmetal and lower for individual REM.

During plating time, the temperature has to be maintained – hence, the required plating time, which is a function of the amount of material processed, is approximately proportional to the energy requirement for heating (if the initial warm-up is neglected). Unlike in the lab experiment, in industrial electrolysis processes, the heat is provided by the same power source as the decomposition current. For the Chinese "3kA technology", the current state-of-the art rare-earth reduction technology, around three quarters of the total energy is used for obtaining and maintaining the temperature, while only 26% is attributable to the decomposition current (Siming et al., 2011; Vogel et al., 2015; Vogel et al., 2016). Heat is lost through various routes; a detailed heat balance calculation is presented in Siming et al., (2011). The energy consumption range reported in the literature was adopted in this study. The value given in the literature refers to the REE output and is reported in kWh/kg REM produced. It was assumed that in the case of a low recovery rate (50 % assumed) the processing of the magnet would take the same amount of time as in the case of a higher (95 % assumed) recovery rate, with approximately half the yield. Due to the fact that most of the electricity is attributable to heat loss, which is related to the process duration, and since it is not clear what additional side reactions would occur, it is assumed that the energy values given in the literature correspond to the rare earth content in the magnet, rather than the fraction recovered at the cathode. This means that the electricity consumption per unit of REM alloy during the electrolysis roughly doubles for the lower recovery rate.

Material consumption and disposal (including auxiliaries and infrastructure)

According to Vogel et al. (2015), the 3kA cell infrastructure is typically replaced every five months. In this period, around 10t (8,5-11,5t) of REM are produced (Vogel et al., 2015). It was assumed that the complete infrastructure, including the electrolytes and outer structure, is replaced.

Literature data was used as a basis for an estimate of the net electrolyte consumption. This estimate in the literature states that the net usage of LiF corresponds to approximately 1-1.5% of the REM output weight (Siming et al., 2011). This is in line with the figures reported for similar processes elsewhere in the literature: Sprecher (2014b) published a dataset for primary rare earth production. According to their dataset, 0,001 kg cryolite is used per kg of liquid Nd in the electrolysis process, and 0.01kg of aluminium fluoride. Their estimates were based on aluminium reduction process data which they adjusted, based on differences in molecular weights. According to the dataset, the total net salt consumption (aluminium fluoride and cryolithe) amounts to 1.3 weight percent of the REM content processed. In aluminium production, the cryolithe consumption is around 0.05 and 1.75 weight percent of the output weight of the recovered aluminium, respectively (Althaus et al., 2007; The Aluminium Association, 2013).

Emissions

Contrary to primary REE production, the recycling process causes no hydrogen fluoride emissions during the anodic reaction, since instead of the graphite anode, an iron anode is used (Equation 3). Since the recycling process is conducted under argon atmosphere, it is assumed that no carbon dioxide or monoxide is emitted. Perfluorocarbon (PFC) emissions are an issue in aluminium production, and there is indication that they present an issue in primary rare earth production, too – see 7.7.2. In the recycling process, no carbon/graphite anodes are employed. The crucible is typically made from graphite, thereby introducing carbon into the cell. Alternative materials which could withstand the corrosive nature are more expensive. However, the pathways which produce PFC emissions in aluminium reduction cells all refer to the anode(s) per se (Wong et al., 2015). Therefore, it was assumed that no PFC emissions are generated from the recycling process.

Assumptions metal scrap recycling

Regarding the EOL magnet, no burdens from the first life of the magnet (production of the original magnet) are assigned to the scrap magnet entering the system. The iron which is left over after the electrolysis from the magnet scrap is not credited[28].

Table 22: Inventory of the recycling process – pre-treatment steps (extraction, cleaning and milling of magnet material, production of 1 kg milled EOL magnet), own estimates based on various sources

Processing step	Input description	Amount – optimistic estimate	Amount – pessimistic estimate	Unit	Source/ assumptions[29]	Dataset
Extraction	EOL magnet weight in compound	1.01	1.1	kg/kg extracted, cleaned and demagnetized magnet	1% lost in removing magnets from rotor, 0,1% lost during cleaning/polishing 0-10% lost during milling (optimistic – pessimistic estimate, based on info from lab experiments).	N/A
	Extraction of magnet from compound - electricity consumption	0.0009	0.0009	MJ/kg milled magnet		Electricity, medium voltage | market group for electricity, medium voltage – GLO

[28] Alternatively, counter-intuitive results would be obtained in the resource depletion category (ADP), where a lower recovery rate during the electrolysis would yield a better ADP results (due to the credits allocated to the iron scrap).

[29] Own estimates which roughly correspond to assumptions in Walachowicz et al. (2014).

Demagnetization	Demagnetization of magnet - electricity consumption	1.1	2.5	kWh/kg magnet	The lower estimate corresponds to demagnetization with infrared, the higher to thermal demagnetization.	electricity, medium voltage | market group for electricity, medium voltage – GLO
Cleaning	Cleaning of magnet with silicon carbide – silicon carbide consumption	0.1	0.2	kg/kg milled magnet	Assuming 10-20% of magnet weight as an estimate. The kg CO_2 emissions per kg magnet (GWP 100a) cleaned from SiC roughly correspond to its contribution in the MoRe report.	Silicon carbide | market for silicon carbide
	Cleaning of magnet with silicon carbide – silicon carbide disposal	0.1	0.2	kg/kg milled magnet		
	Cleaning of magnet with silicon carbide – electricity consumption	1.17	1.17	MJ/kg milled magnet		
	Polyphenylene sulfide granule consumption	0	(0.003)	3g/ kg magnet	The material is reusable and therefore not taken into account. Even if it is not reused, the quantity used per kg of magnet is very small.	
	Polishing - electricity consumption	0.008	0.008	MJ/kg milled magnet		
Milling (only process variant with milling)	Ball milling material loss	0% material loss, based on information from Enrique Herraiz (Nd hydrate	10% material loss, based on information from Recai Önal	kg/kg milled magnet	The material loss is estimated between 0 and 10 weight %. It is assumed that the material is landfilled.	

		milling)					
	Ball milling – electricity consumption	0.007 – lower estimate	0.06 – higher estimate	kWh/kg milled magnet	(Metso, 2015; Taylor, 1949; Tsakalakis and Stamboltzis, 2004a; Tsakalakis and Stamboltzis, 2004b; Tsakalakis and Stamboltzis, 2008) The hardness of Nd-Fe-B is around 600 (Vickers hardness) or 5 (Moh's hardness) The lower estimate was calculated for a or reduction from 500 to 200 microns with ball-milling (Tsakalakis and Stamboltzis, 2004a; Tsakalakis and Stamboltzis, 2004b). For a high estimate, 0,06 kWh/kg was assumed, based on the energy consumption reported for ball-milling in cement production (Tsakalakis and Stamboltzis, 2008)	
	Ball milling – argon consumption	0.2	0.6	kg/kg milled magnet	This was based on the nitrogen consumption for ball-milling during sintered magnet production (data from Enrique Herraiz / Magneti) and adjusted based on the ratio of molecular weights of argon and nitrogen		
	Outputs						
(Only process variant with milling)	Ball milling – milled magnet powder, ca 200 micron	1	0.9		kg milled magnet	Reference flow	
(Only process variant without milling)	Cleaned and demagnetized magnet	1	1		kg cleaned and demagnetized magnet	Reference flow	

Table 23: Inventory recycling process – electrolysis (extraction of REM from EOL magnet material, production of 1 kg secondary REM alloy)

Input description	Amount – optimistic estimate	Amount – pessimistic estimate	Unit	Data source
Carbon lining	0.0005	0.0005	kg graphite / kg REM	Carbon lining is commonly used in REE electrolysis (Vogel et al., 2015). graphite, battery grade | market for graphite, battery grade APOS U, GLO Figure is an own estimate, corresponds to 5kg replaced in 5 months
DC electricity consumption (current used to drive the decomposition reaction)	9	13	kWh / kg REM alloy produced from EOL magnet	Based on data from Siming et al., 2011; Vogel et al., 2015 electricity, medium voltage | market group for electricity, medium voltage - GLO
Argon	0.0015	0.0015	kg/kg REM	Figure from (Sprecher et al., 2014b) Data for electrolysis step during primary production of REM
EOL Nd-Fe-B magnet, cleaned (milled) and demagnetized	3.4	6.45	kg magnet /kg REM	Calculated from Vogel et al., 2015, who provide info on monthly output quantities for REM reduction. EOL-magnet material calculated from average 31% REM content in Nd-Fe-B material and efficiency of 50% (pessimistic) to 95% (optimistic)
LiF	0.01	0.015	kg LiF / kg REM	This consumption range is reported in Siming et al. (2011) Lithium fluoride – market for lithium fluoride GLO
LiF waste with Nd-Fe-B impurities	0.01	0.015	kg/kg REM deposited	Same as LiF input weight. LiF is characterized by acute toxicity in rats and hazardous to drinking water hazardous waste, for incineration | market for hazardous waste, for incineration
NdF	0.01	0.015	kg ReF/kg REM	This data is reported in Siming et al. (2011) for ReF consumption No NdF dataset exists. Nd oxide was modelled as a proxy.

				Market for Neodymium oxide, GLO
Molybdenum cathode	0.0001	0.0001	kg molybdenum/kg REM	Own estimate, corresponds to 1kg molybdenum replaced in 5 months. Molybdenum is inert but since the process is conducted at "low" temperatures, the cathodic product is in solid state and needs to be removed mechanically from Mo, hence the cathode is damaged **Molybdenum – market for molybdenum - GLO**
Iron anode (only process variant with milling – in the process variant without milling, the scrap magnet is used directly as anode)	1	2	kg / kg REM	The theoretical consumption (Equation 4) is 0.4 kg per kg Nd, based on the molecular weights of Fe and Nd. It was assumed that the Fe consumption will be around 1 to 2 kg per kg REM deposited. **Steel, low-alloyed, steel production, electric, low-alloyed**
Infrastructure: building where electrolysis takes place	1.5385E-10	1.5385E-10	kg/kg REM	**Aluminium electrolysis, facility [RER]** figure and dataset choice is adopted from aluminium production, primary, liquid.
Shell (which is made from steel in the case of aluminium production cells)	0.0039	0.0039	kg/kg REM	Reinforcing steel figure is taken from aluminium production, primary, liquid. The figure (taken from the ecoinvent dataset) corresponds to the replacement of 39 kg of steel every 5 months. **Reinforcing steel, market for reinforcing steel, GLO**
Asbestos layer	0.0039	0.0039	kg/kg REM	Market for asbestos, chrysotile type. In absence of quantitative data, it was assumed that the asbestos layer weighs approximately the same as the steel layer. The figure is taken from aluminium production, primary, liquid. The figure (taken from the ecoinvent dataset) corresponds to the replacement of 39 kg of asbestos every 5 months. **Asbestos, crysotile type, market for asbestos, crysotile, GLO**

clay used to line the oven (DS used to model bricks)	0.00986	0.00986	kg/kg REM	Refractory, fireclay, packed, figure is taken from aluminium production, primary, liquid. This figure (taken from the ecoinvent dataset) corresponds to the replacement of 100 kg of bricks every 5 months. **Refractory, fireclay, packed, market for refractory, fireclay, packed, GLO**
brick disposal	0.00087	0.00087	kg/kg REM	Inert waste, for final disposal - figure and dataset choice is based on aluminium production, primary, liquid. Figures adopted from ecoinvent. **inert waste [kg]**
brick disposal	0.00463	0.00463	kg/kg REM	Inert waste, figure is taken from aluminium production, primary, liquid. Figures adopted from ecoinvent. **inert waste, for final disposal [kg]**
Asbestos disposal (inert waste)	0.0039	0.0039	kg/kg REM	Inert waste, for final disposal [kg]
Output				
REM (Nd/Pr) alloy, deposited at cathode in layers	1	1	kg	Reference unit.
Nd-Fe-B magnet material after REM extraction (FeB, unreacted Fe from anode , rare earth fraction not deposited at cathode)	3.45	7.45	kg/kg REM deposited	Figure was calculated as follows: difference (milled/unmilled) magnet weight plus weight of anode consumed (for scenarios with milled magnet only) minus rare earth metal weight deposited at cathode iron scrap, unsorted | steel production, electric, low-alloyed (credited only for fraction from anode)

scrap steel	0.00857	0.00857	kg/kg REM	steel liner scrap, figure and dataset taken from aluminium production, primary, liquid (ecoinvent DS) scrap steel | market for scrap steel (modelled as negative input)
Molybdenum for recycling	0.0001	0.0001	kg molybdenum per kg REM	Molybdenum is likely to be recycled. It is often alloyed with steel.(Asian Metal, 2016b)

7.7 Life cycle inventory – primary production – assumptions

7.7.1 Data assumptions

The recycling process is compared against the primary production of rare earth metals from mineral deposits rich in light rare earths. Life cycle inventory datasets for this processing step have previously been compiled (Jamieson, 2014; Schreiber et al., 2016; Sprecher et al., 2014b). Process-relevant parameters (energy and / or material consumption) are also reported outside the life cycle assessment literature (Talens Peiró and Villalba Méndez, 2013; Vogel et al., 2015). The last step in the rare earth metal production process is associated with high energy requirements, most of which are accountable to heat losses (Siming et al., 2011).

One noteworthy difference between the information provided in the existing datasets and the literature outside LCA is in the recent paper by Vogel et al. (2016), who report emission factors for PFCs based on findings from lab-scale experiments. The values for PFC emissions given in the published life cycle inventories for rare earth electrolysis (Schreiber et al., 2016; Sprecher et al., 2014b) are much lower than the emission factors given in Vogel et al. (2016). Jamieson (2014) do not list any PFC emissions in their inventory. In practice, the emission factors depend on whether the operating conditions are managed in a way that the unintended anodic reactions can be avoided.

In this study, the primary production of rare earth oxides is based on the data from Sprecher et al. (2014b) (baseline scenario only). The data for the electrolysis step is provided in the original publication and therefore not repeated here. The baseline dataset was adjusted as indicated in Table 24 to account for the wide range of PFC emission data reported in the literature, and the range in electricity consumption values reported.

There are two stages in the primary production of rare earths for which assumptions regarding co-productions are necessary: the beneficiation stage, where concentrated iron ore and rare earth concentrate are separated, and the solvent extraction stage undertaken to separate individual rare earths. Value allocation was used to share the process impacts from both multi-output processing stages. For the beneficiation stage, around (72%) of the output value is attributable to the mixed rare earth concentrate, and around 82% of the rare earth value after separation is attributable to the “magnet REE”, i.e. Nd and Pr.

Table 24: Modifications to the LCI provided in Sprecher (2014b) – reduction of rare earth oxides in molten salts

Input modified	Amount – optimistic estimate	Amount – pessimistic estimate	Unit	Data source
Energy consumption during electrolysis	9	13	kWh/kg REM	The energy consumption range is based on data from Siming et al., 2011; Vogel et al., 2015 electricity, medium voltage | market group for electricity, medium voltage – GLO This has been changed from the Sprecher dataset to align the assumption with those for the recycling process.
Output modified	**Amount – optimistic estimate**	**Amount – pessimistic estimate**	**Unit**	**Data source**
C_2F_6	0.000001	0.0116 kg C_2F_6	kg/kg REM	(Schreiber et al., 2016) for low estimate, (Vogel et al., 2016) for high estimate
CF_4	0.00001	0.0739 kg	kg/kg REM	(Schreiber et al., 2016) for low estimate (Vogel et al., 2016) for high estimate

7.7.2 Perfluorocarbon (PFC) emissions

Perfluorocarbon emissions are potent and *very* long-lived greenhouse gases associated with aluminium and semiconductor production (IPCC, 2013). During aluminium electrolysis, PFCs are formed in unintended side reactions when the fluorine from the salt bath reacts with the carbon from the anode. Similar effects also occur during rare earth reduction, where graphite anodes are also state of the art (Lucas et al., 2015). The effects are however far less discussed compared to the PFC emissions from aluminium and semiconductor production, since the global production volumes for rare earth metals are small – see e.g. Kim et al., (2014); Wong et al., (2015).

In recent years, a noticeable gap between reported and measured PFC emissions has emerged, and efforts are being made to improve emissions accounting for PCFs from aluminium production (IPCC, 2013; Mühle et al., 2010; Wong et al., 2015). The authors of a recent study claim that PFC emissions

from rare earth reduction have so far very likely been underestimated. Based on off-gas measurements in the lab taken from a setup similar to the industrial realization, they estimate PCF emissions of approximately 0.0739 kg CF_4 and 0.0116 kg C_2F_6 per kg rare earth metal (Nd) (Vogel et al., 2016). Since these substances have global warming potentials of 6630 and 11100 times the magnitude of CO_2 over a 100-year period (IPCC, 2013), small contents in the off-gas can have very large effects: the estimates by Vogel and co-workers amount to 619 kg CO_2 equ./kg REM, which is tremendous compared to the reported 0.1-3 t CO_2-equ. of PFC emissions per kg aluminium (World Aluminium, 2016b). According to own calculations, this would mean that rare earth production makes a contribution of *very roughly* 10% of CO_2-equivalent emission from PFCs (2010 estimates)[30]. It should be noted that the emission factors are estimated based on lab-scale experiments, and need to be validated in an industrial setting. PFC emissions cannot be captured once released, so the formation has to be managed via the control of process conditions (Vogel et al., 2016). Both in aluminium and rare earth production, the formation processes are complex and influenced by a multitude of factors (Vogel et al., 2016; Wong et al., 2015). Vogel and co-workers are developing an automated process to help reduce these emissions. A patent has been filed to address this issue back in 1998 (Keller and Larimer, 1998) – see also Keller, (1998); but a later patent claims the design by Keller and Larimer is impracticable (Keniry and Kjar, 2013). Elsewhere in the literature, PCF emissions associated with rare earth production are also acknowledged as an issue which merits further investigation (Li et al., 2014; Trudinger et al., 2016). Inert anodes (which would eliminate the carbon anode), combined with new types of electrolytes, are a research topic in molten-fluoride electrolysis (MPC, 2017; Wang et al., 2013).

7.7.3 Hydrogen fluoride (HF) emissions

Hydrogen fluorides are produced during aluminium production and during rare earth electrolysis (Siming et al., 2011; World Aluminium, 2016a). When contacted with water vapour, hydrogen fluoride forms hydrofluoric acid. Both the gas and acid are toxic to humans, marine and freshwater species. Fluoride emissions can be managed via process control and through the use of fume control systems (World Aluminium, 2016a). In aluminium production, HF emissions can be efficiently scrubbed with a very high efficiency of ca. 99% (Paulin et al., 2009). Details on the management of hydrogen fluoride (HF) emissions from rare earth electrolysis could not be found in the literature; however, they are mentioned in the literature as an issue (Wang et al., 2013). According to Vogel et al. (2016) and Schreiber et al. (2016), in rare earth production, the emissions are managed via scrubbing. Siming (2011) reports that HF emissions in rare earth electrolysis are being addressed by the development of new cell designs. The figure provided in Sprecher et al., (2014b) was adopted.

7.8 Results

The life cycle impact assessment was conducted with CML baseline. Results are shown for a selection of impact categories only, namely ozone depletion, human toxicity, depletion of abiotic resources (elements, ultimate reserves), acidification, depletion of abiotic resources (fossil fuels), photochemical oxidation, climate change, and eutrophication. The results from the ecotoxicity categories are not shown in Table 25, which is justified in the next section.

7.8.1 Comparing the proposed recycling process against primary rare earth production

The results of the recycling route were compared against the most common primary production route for Nd and Pr, i.e. rare earth production from LREE-rich mineral deposits (i.e. bastnaesite/monazite

[30] This was calculated based on the annual emissions for C_2F_6 and CF_4 reported (around 2 and 12 kt, respectively in 2010) (Kim et al. (2014); Trudinger et al. (2016)); GWP-100a CO_2 eq. factors reported in IPCC (2013) (11100 and 6630, respectively), REM production for use in magnet manufacturing reported in EC (2014) (23 kt REM in 2012).

deposits) (Sprecher, 2014b)[31].Results show that recycling is beneficial for all impact categories and scenarios shown in Table 25. Results for the impact categories terrestrial, freshwater and marine ecotoxicity did not confirm this trend for all scenarios. However, the contribution analyses conducted for these categories raised some doubts about the results. For example, for the category terrestrial ecotoxicity, the production of REM from the recycling route was associated with higher impacts than primary production when the high (pessimistic) LCI estimate recycling scenarios with milling. Results show that for the recycling scenarios with milling, this category is dominated by the steel used for the iron anode. (This steel is not required for the scenarios where the scrap magnet is directly used as anode.) The impact is largely from chromium emissions to air during steel production, although a low-alloyed steel dataset was used here (as a proxy for silver steel). This result is very questionable for two reasons: First, the steel consumption is based on a conservative assumption, i.e. a very generous amount of steel was assumed, especially for the high (pessimistic) LCI estimate (see Table 23). Second, and most importantly, the addition of chromium to the steel is not crucial for this application.

Besides the findings from the contribution analysis, it should be noted that the ecotoxicity categories (terrestrial, freshwater and marine ecotoxicity) are reportedly associated with high uncertainties JRC, (2011), and therefore often omitted by LCA practitioners.

[31] See also footnote 26.

Table 25: Recycling vs. primary production: Comparing environmental impacts between recycling and primary production for different scenarios (impact per kg Nd/Pr alloy and % difference impact recycling / impact primary production per kg Nd/Pr alloy)

	One-step recycling process, 1 kg REM, Low ESTIMATE				One-step recycling process, 1 kg REM , high ESTIMATE			
	with milling		without milling		with milling		without milling	
Impact category (based on CML baseline)	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery
Ozone layer depletion (kg CFC-11 eq.)	1.62E-06	9.27E-07	1.34E-06	7.44E-07	3.19E-06	1.88E-06	2.34E-06	1.29E-06
Human toxicity (kg 1,4-dichlorobenzene eq.)	20	15	12	7	39	30	20	12
ADP - elements, ultimate reserves (kg Sb-eq.)	4.92E-05	4.29E-05	2.31E-05	1.78E-05	9.08E-05	8.32E-05	3.54E-05	2.55E-05
Acidification potential - average Europe (kg SO2 eq.)	0.15	0.08	0.13	0.07	0.30	0.17	0.22	0.12
Depletion of abiotic resources - fossil fuels (MJ)	302	168	253	136	603	347	450	242
Photochemical oxidation - high Nox (kg ethylene eq.)	0.0072	0.0042	0.0056	0.0030	0.0146	0.0089	0.0104	0.0055
Climate change - GWP100 (kg CO2 eq.)	30	17	25	13	59	34	44	23
Eutrophication - generic (kg PO4--- eq.)	0.06	0.04	0.05	0.03	0.12	0.07	0.09	0.05
	Low LCI estimate recycling /Low LCI estimate primary production				High LCI estimate recycling /Low LCI estimate primary production (% change)			
	with milling		without milling		with milling		without milling	
Impact category (based on CML baseline)	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery
Ozone layer depletion (% change)	11%	6%	9%	5%	21%	13%	16%	9%
Human toxicity (% change)	3%	3%	2%	1%	7%	5%	3%	2%
ADP - elements, ultimate reserves (% change)	9%	8%	4%	3%	16%	15%	6%	5%
Acidification potential - average Europe (% change)	22%	12%	19%	10%	43%	25%	32%	17%
Depletion of abiotic resources - fossil fuels (% change)	27%	15%	23%	12%	54%	31%	40%	22%
Photochemical oxidation - high Nox (% change)	26%	15%	21%	11%	53%	32%	38%	20%
Climate change - GWP100 (% change)	40%	23%	34%	18%	80%	46%	59%	31%
Eutrophication - generic (% change)	51%	30%	41%	22%	100%	59%	71%	38%
	Low LCI estimate recycling /high LCI estimate primary production (% change)				High LCI estimate recycling /high LCI estimate primary production (% change)			
	with milling		without milling		with milling		without milling	
Impact category (based on CML baseline)	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery	50% recovery	95% recovery
Ozone layer depletion (% change)	11%	6%	9%	5%	21%	12%	9%	16%
Human toxicity (% change)	3%	3%	2%	1%	7%	5%	2%	3%
ADP - elements, ultimate reserves (% change)	9%	8%	4%	3%	16%	15%	5%	6%
Acidification potential - average Europe (% change)	21%	12%	18%	10%	42%	24%	17%	31%
Depletion of abiotic resources - fossil fuels (% change)	26%	15%	22%	12%	52%	30%	21%	39%
Photochemical oxidation - high Nox (% change)	25%	15%	20%	11%	52%	31%	20%	37%
Climate change - GWP100 (% change)	4%	2%	4%	2%	8%	5%	6%	3%
Eutrophication - generic (% change)	50%	29%	40%	22%	97%	58%	69%	37%

7.8.2 Contribution analysis GWP 100a

Metal production is an important contributor to global warming (Nuss et al., 2014). It is therefore important to understand to what extent recycling processes provide an advantage regarding this issue over primary production (see e.g. Abbasalizadeh et al., 2017; Gauß et al., 2015). For this study, the focus is on identifying the environmentally important parameters in process development.

Against this background, a contribution analysis for GWP 100a is presented. Results refer to the production of 1 kg Nd-Pr (alloy). For the recycling processes, a contribution analysis for the best and the worst case scenario is presented.

The best case recycling scenario is the low (optimistic) LCI estimate with 95% material recovery during electrolysis and without milling. 57% are attributable to the electrolysis, of which 54% of the contribution is attributable to the production of electricity used for the electrolysis, and 3% for material and infrastructure (Nd oxide, LiF, etc.). A surprisingly large contribution is from the pre-processing (43%, of which 22% is attributable to demagnetization, and 18% to silicon carbide used for cleaning). For the worst case recycling (high (pessimistic) LCI estimate, 50% REE recovery, with magnet milling)), only 40% are attributable to the electrolysis (33% electricity for electrolysis), and the other 60% to cleaning with silicon carbide and demagnetization.

For the low (optimistic) LCI estimate of the primary production process, around 15% of the impact (GWP 100a) is from the electrolysis step, of which 0.5% is from direct emissions of CO_2, and 0.5% from upstream process emissions of this processing step (infrastructure, salt etc.). The other 14% are attributable to electricity consumed for the electrolysis process step. Around 85% are attributable to the processing steps before the electrolysis (mining, beneficiation, roasting, leaching, solvent extraction). For the high (pessimistic) LCI estimate of the primary production process, 89% of the GWP 100a impact is attributable to direct emissions from the electrolysis process, with only 2% attributable to the electricity consumption in the electrolysis process, and 9% attributable to the production of the rare earth oxides. These differences illustrate the relevance of a more detailed investigation into the PFC emissions.

7.8.3 Sensitivity of LCIA results to different factors

Primary rare earth production

For the primary rare earth production, an optimistic and a pessimistic variant of the LCI dataset were modelled. A single baseline dataset was used as a reference for the primary production. The only differences between the optimistic (low) and pessimistic (high) LCI estimates stem from the changes in this baseline dataset – the electricity consumption during the electrolysis and the PFC emissions. The electricity consumption causes differences between 0 and 6% between the low and high estimate across the impact categories. The PFC emissions only impact the results in category GWP 100a, but for this category, the results are extremely sensitive to the PFC emission estimates, with a factor 9 between the optimistic (low) and pessimistic (high) LCI estimate.

Recycling

For the recycling process, an optimistic and a pessimistic variant were modelled as for primary production. In addition, the scenarios were varied with regards to the inclusion of a milling step, and regarding the recovery rates.

When comparing the pessimistic (high) LCI estimates against the optimistic (low) estimates for the recycling process, the impact assessment results roughly double compared with the low estimates for each scenario pair and impact category considered. The LCI estimates entail a large variation between optimistic (low) and pessimistic (high) LCI estimates for the impact of the pre-treatment steps. These show especially for the scenarios with the low recovery rates, which enhance those differences. Within the pre-treatment steps, factors which noticeably impact the results include the energy consumption for demagnetization, the assumed argon consumption, material losses assumed for the milling process, and the quantity of silicon carbide used for magnet cleaning.

The influence of the inclusion of a milling step on the environmental impacts of the recycling process was also tested. The influence of adding a milling step to the recycling process is 30% on average for most impact categories (not including the toxicity categories). The category abiotic resource depletion, elements, is also particularly sensitive to the inclusion of the milling step, which can be explained by some of the components in the steel used as anode material in the milling scenarios.

The results are, not surpringly, sensitive to the recovery rate. As an optimistic estimate, it was assumed that 95% of the rare earth elements can be recovered during the electrolysis step. If the recovery rate was substantially lower (50% is assumed), the impacts per kg Nd-Pr alloy increase approximately by 70% (average) which varies depending on the impact category and scenario considered. For the impact category GWP 100a, the difference is relatively large at around 80%.

7.9 Summary and conclusion

A life cycle assessment study was conducted for a one-step molten salt electrolysis process employed for the recycling of rare earths from scrap magnet material. The study was conducted to identify potential environmental hotspots early on during the process development, and to see how the potential impacts of this secondary rare earth production route would compare against the impacts of the primary production routes.

The comparison of this recycling route with primary production shows that the recycling process has the potential for much lower process-specific impacts when compared against the current rare earth primary production route. The recycling process is at an early development stage – so far, the main focus has been on demonstrating that the process works in principle. Therefore, the influence of different processing choices and data assumptions on the results was tested. Even when a low REE recovery rate of 50% during the electrolysis is assumed, the recycling process is environmentally beneficial. Results show that the material recovery rate is crucial to the overall impact of the recycling process. Furthermore, the choice of preparation steps also influences the overall impact - in contrast to the cell infrastructure which has been included in the study due to a relatively frequent need for replacement (every 150 days), but does not have a big impact on the overall results. For the preparation steps, data assumptions could be further refined. For the cleaning step in particular, which does not appear to be negligible in terms of impact contribution, it is recommended to further investigate what level of cleaning is actually necessary before the electrolysis.

The inclusion of the milling step can play a role, but the difference is particularly large for the toxicity categories, and due to the composition of the iron anode rather than the milling itself. The ecotoxicity categories are characterized by high uncertainties, and the additives in the steel which drive the impact are not necessarily required in the anode material. It must be highlighted here that the purpose of the inclusion of the milling step is to increase the material recovery rate of the process. To what degree this happens could not yet be considered in these scenarios, since this had not been analysed quantitatively at the time of writing; i.e. the milling step and the material recovery rate were modelled as if they were independent. However, this is an important knowledge gap without which it is difficult to

draw conclusions about whether the magnet should be milled or not prior to the electrolysis from an environmental impact point of view. Process development should focus on optimizing material recovery, and investigate to what extent milling improves the recovery rates.

Literature focussing on technical process improvement in rare earth primary production mentions potentially large additional impacts from primary rare earth production which are not yet discussed in LCA literature. The uncertainties associated with these potential impacts stem from the fact that PFC emissions from the rare earth industry are currently not reported, but have very high global warming potentials. Hence even small quantities emitted make a large contribution to the impact. The issue warrants further investigation. Also, investigations into unaccounted PFC emissions from aluminium production indicate that those could be a bigger issue with increasing cell size (Wong et al., 2015). A trend towards larger cells is also observed in the rare earth industry (Vogel et al., 2015). For these reasons, a closer investigation of this phenomenon is recommended. If this is shown to be an issue, rare earth producers should be encouraged to report PFC emissions, as is done by aluminium manufacturers (Wong et al., 2015).

Due to the early stage of process development, the results from this Chapter should be interpreted as early estimates that can serve as a basis for further investigations. However, the Chapter has highlighted some interesting questions which should be further investigated when evaluating environmental impacts of rare earth production.

Chapter 8 - Summary of findings, discussion and conclusion

8.1 Major Findings

The demand for rare earths for Nd-Fe-B magnet production is increasing; and this trend expected to continue over the next years (Els, 2017). A material flow analysis was conducted to obtain estimates regarding the global availability of Nd-Fe-B scrap magnets for recycling in the near future (Chapter 4). This was based on a detailed analysis of the Nd-Fe-B material used in different applications. For this purpose, different rare earth contents of different Nd-Fe-B compositions were taken into account, as well as manufacturers' efforts to reduce heavy rare earth content in the magnet material.

A global estimation of rare earth recycling potentials, i.e. potential secondary rare earth metal supply from Nd-Fe-B recycling, was calculated for Nd-Fe-B material from EOL appliances and industrial scrap. In addition, a detailed study of Nd-Fe-B application groups was conducted and estimates provided for the ease of collection and extraction. To achieve this, information on expected future demand for Nd-Fe-B magnets, and corresponding REE demand was included. Different magnet compositions and expected compositional changes were both considered in terms of their effects on the demand scenarios.

According to the scenario estimates from this study, around 20% of the demand for individual REE for use in Nd-Fe-B magnet production can be provided from secondary sources in the time period 2020-30. Despite the fact that in absolute numbers, appliances containing Nd-Fe-B magnets will become increasingly available for recycling, the percentage of REE supply from secondary supply is not increasing in the considered time period. This is due to the high demand growth rates for Nd-Fe-B magnets, and the resulting REE demand growth. In other words, according to the model estimates, demand grows faster than the secondary supply.

The detailed analysis included eleven Nd-Fe-B magnet application groups. The results show that the importance of different EOL Nd-Fe-B applications as a source for secondary REE changes over the time period considered. This results in a changing mix of components to be handled by disassemblers, and a variability in material composition to be handled in Nd-Fe-B recycling processes.

The following findings should be highlighted:

- The amount of industrial Nd-Fe-B scrap available for recycling is likely to exceed achievable potentials of secondary Nd-Fe-B extractable from EOL devices in years 2020–30 (by mass of Nd-Fe-B material).

- Results show that around 20% of global demand of Nd/Pr and 22–23% of Dy/Tb for Nd-Fe-B production can be met from secondary sources from EOL magnets and industrial Nd-Fe-B scrap in years 2020–30.

- The most promising Nd-Fe-B application groups were identified from a perspective of Nd-Fe-B scrap available to enter a secondary REE production route. The importance of different application groups changes for that matter over the time period considered.

After quantification of the Nd-Fe-B material available for recycling, a life cycle assessment study was conducted to provide an estimation to what extent recycling of REE could reduce future environmental impacts of the global rare earth production system.

Results show that the avoided impact from primary production far exceeds the impact from the recycling activity for all analysed impact categories. The uncertainties associated with REE quantities

available for recycling, foreground and background datasets do not impact the overall finding. The findings are in line with those of previously conducted attributional LCA studies in terms of the conclusion that REE recycling from Nd-Fe-B is environmentally beneficial over primary production (Sprecher et al., 2014b; Walachowicz et al, 2014). However, it was shown here that this is not only a result of the differences in process-specific impacts of the recycling and primary production processes, but market effects also play an important role.

In particular, this study has quantitatively confirmed the hypothesis that recycling would contribute towards a mitigation of the balancing problem, and the supply of co-products would not be jeopardized if the primary production output was partly replaced by an alternative (secondary) production route. This was based on own quantitative estimates regarding the possible extent of the recycling operation. First, a contradicting statement was investigated, according to which rare earths are produced as by-products. It was shown that this statement is not valid for the most common production routes, namely, Bayan Obo and production from ion-adsorption clay deposits in Southern China. Then, it was determined through a basket price calculation that “magnet REE” are the determining products for these routes, i.e., the production levels are increased when demand increases.

In order to be able to quantify the potential environmental impacts of REE recycling, a life cycle inventory dataset was compiled for REE production from ion-adsorption clay deposits. Rare earth production from ion-adsorption clay deposits constitutes one of the most important rare earth production routes, and the most important production route for heavy rare earths such as dysprosium and terbium today. To achieve this LCI compilation, quantitative and qualitative information on rare earth mining and processing for this route was compiled from the literature and with help from industry experts. A detailed review of the literature on environmental impacts associated with this mining and processing route is provided, uncertainties associated with the dataset are highlighted, and impacts not covered by the current impact assessment methods are pointed out.

In addition, a life cycle assessment study was conducted to assess the potential environmental impacts of a one-step recycling process developed by researchers in the EREAN project, for the recycling of rare earths from scrap magnet material. The study was conducted to identify potential environmental hotspots early on during the process development, and to see how the potential impacts of this secondary rare earth production route would compare against the impacts of the primary production routes. The influence of different processing choices and data assumptions on the results was investigated. Results show that the material recovery rate is crucial to the overall impact of the recycling process. Furthermore, the preparation steps also contribute to the overall impact. The comparison of this recycling route with primary production shows that the recycling process has the potential for much lower process-specific impacts than the current rare earth primary production routes.

8.2 Importance of the findings and relation to other studies

8.2.1 Potential for secondary REE supply from Nd-Fe-B scrap

Regarding the quantification of recycling potentials, i.e. the potential for secondary supply of rare earths (Chapter 4), various research groups have provided estimates on recycling potentials from scrap Nd-Fe-B magnets for different regions and application groups – see e.g. (Du and Graedel, 2011; Guyonnet et al., 2015; Rademaker et al., 2013; Seo and Morimoto, 2014; Sprecher et al., 2014a; Swain et al., 2015; Zepf, 2015). The study presented here is more comprehensive in scope regarding the types of applications covered, and more detailed than previous studies. At the time of writing, it was the only study which has quantified expected changes in magnet composition in a recycling potential context.

The “European Rare Earths Competency Network“ (ERECON) put together a list of priority products for which Nd-Fe-B recycling is most likely to become economically viable - see ERECON (2015). The ERECON priority list includes hard disk drives, automotive applications, motors used in industrial applications, acoustic transducers, air conditioners, mixed electronics, electric bikes, and wind turbines. In terms of EOL magnets expected to become available for recycling, quantified in this study for 2015 and 2020, one would expect electric two-wheelers and magnetic separators to appear higher up on the ERECON list. However, the differences in results could be explained by the difference in geographical focus: the findings from the ERECON report have a European focus, whereas this study was global in scope. At least for electric two-wheelers, the majority of EOL products arise outside Europe, so differences can be expected in the priority ranking of Nd-Fe-B products.

8.2.2 Life cycle inventory for the production of rare earths from ion-adsorption clay deposits

The life cycle inventory compilation on rare earth production from ion-adsorption clay deposits and processing builds on an existing study, which, however, is only representative of the production of a rare earth concentrate (Vahidi et al., 2016). The separation stage was not included in this study. To our knowledge, a life cycle inventory dataset representative of the most common heavy rare earth production route was previously not publicly available at the time of writing – neither in the life cycle inventory databases available for purchase, nor in academic or grey literature.

The demand for dysprosium has experienced substantial growth in recent years, mainly due to its use in neodymium-iron-boron (Nd-Fe-B) magnets, the demand for which is increasing largely due to their use in efficient motor applications. Hence, the analysis of environmental impacts associated with rare earth mining and processing of ores rich in dysprosium is gaining importance. The knowledge about rare earth production from ion-adsorption clay deposits is improved by providing a life cycle inventory dataset which comprises rare earth mining and processing to individual oxides. This dataset and the qualitative information supporting the LCI data together fill an important gap. Furthermore, the findings should encourage a more detailed investigation of local environmental impacts which occur from ion-adsorption clay deposit mining.

8.2.3 A consequential LCA study to assess the effects of Nd-Fe-B magnet recycling on the balancing problem inherent to the rare earth market

The consequential LCA study provides an example of how effects on an unbalanced (raw material) market can be addressed in LCA studies. This topic has not previously been the focus of other LCA studies.

Previous (attributional) LCA studies on rare earth recycling focused on process-specific impacts. They have applied economic or mass allocation to divide the impact of primary rare earth production between individual elements (Jin et al., 2016; Sprecher et al., 2014b; Walachowicz et al., 2014). Economic allocation distributes the impact amongst the joint products, based on market value and production ratio. However, REE production is characterized by a large gap between supply and demand for some elements (EC, 2014). Economic allocation does not distinguish between the fraction of co-products that is sold, and the fraction that is stockpiled.

To assess the possible effects of a decision on the flows of a system, consequential LCA studies are employed (Finnveden et al., 2009). C-LCA studies typically take market effects into account (Zamagni et al., 2012). The introduction of a recycling system is expected to mitigate the balance problem (Binnemans and Jones, 2015). Hence, market effects are foreseen and intended, and a consequential modelling approach is appropriate.

To date, consequential LCA studies on rare earth recycling have not yet been conducted. However, a background dataset is available in the life cycle inventory database ecoinvent V.3. The “substitution, consequential, long-term” model assumes that all rare earth elements produced from bastnaesite concentrate are determining products, since there are no alternative production routes. This means that an increase in demand for one element therefore leads to an increased consumption of the co-products (i.e., market clearance is assumed). This is done via a direct link to the marginal consumption activities affected (see Weidema et al., 2013). However, this model did not take into account the option to stockpile, which is commonly practiced for rare earths produced in oversupply, and which contradicts the assumption of market clearance. Hence, the model is not suited to address the impacts of a decision to introduce Nd-Fe-B recycling on an imbalanced rare earth market.

The model presented in ecoinvent could be of merit in situations where supply does ***not*** meet demand for the determining products in a given year (e.g. Nd) (and where using stockpiles as a source is not an option), but instead, the increasing demand for one application is compensated by a reduction in demand elsewhere due to supply restrictions. One would then need to identify where on the market less Nd could be used; and which applications are less likely to do so. This question is also an interesting one, since the possibility of tight supply-demand balances have been discussed for some of the REE, and substitution is actually happening. In particular, for Dy and Nd used in Nd-Fe-B magnets, cerium is trialed as a replacement.

Alternatives to the current Nd-Fe-B magnets include

- The use of different elements (e.g. when replacing Nd by cerium (here, a different functionality would need to be considered, i.e. a 1:1 replacement is unlikely)
- a different magnet material (different microstructure but still Nd-Fe-B, with a composition that uses less of the element with the tight supply situation)
- other permanent magnet materials (e.g. Sm-Co)
- other motor components (e.g. induction motors instead of permanent magnet motors)
- or even substitutes at product- or service level.

If the main substitution route is at the element level, the model proposed in ecoinvent could be useful. However, for REEs, other supply chain levels may be more relevant in practice for reducing critical rare earth demand: Due to their unique properties, the replacement at element level is not easy. Recently, energy saving lamps which relied on the availability of europium, terbium and yttrium, were being replaced by LEDs, which require smaller quantities of REE. In these cases, it would be advisable to identify the most relevant substitution path, i.e. to consider which level in the supply chain is most likely going to react to the tight supply-demand balance. Although this would require a larger expansion of the system than when focusing only on element substitution, it is likely to give more realistic results.

8.2.4 Process-specific impacts of other recycling technologies: a one-step recycling process using molten salt electrolysis

This Chapter presented an initial life cycle assessment study for an Nd-Fe-B recycling process which uses molten salt electrolysis to extract REE from magnet scrap. The importance of this chapter is twofold: Firstly, it is supports the development of the process with regards to its environmental impacts: The results illustrate that the main focus should be on achieving higher recovery rates. Secondly, the study has highlighted an important uncertainty associated with the dataset for primary rare primary production, which stems from the fact that perfluorocarbon emissions from the rare earth industry are currently not reported, but have very high global warming potentials. Hence, even small quantities emitted can make a large contribution to the impact, and the issue warrants further investigation. Although this has been suggested outside the LCA literature, it has not yet been investigated in the con-

text of LCA studies. However, if PFC emissions are an issue, they need to be considered in future life cycle assessment studies on rare earth metal production, or on products which require rare earth metals as input materials, such as Nd-Fe-B magnets and other REE alloys.

8.3 Limitations and suggestions for further research

The following two sections discuss the shortcomings of LCIA methods regarding the assessment of ionizing radition and resource depletion – both of which are important issues for this study. Ionizing radiation is an issue associated with many primary rare earth production routes which needs to be appropriately managed.

8.3.1 Ionizing radiation

Mineral rare earth deposits contain varying concentrations of radioactive material, namely thorium (200-40 000 ppm) and uranium (10-370 ppm) (Schmidt, 2015b). Uranium decay products with environmental/ human health relevance include e.g. Ra-226, Rn-222, Pb-210 and Po-210. Thorium-228 decays into the radioactive Ra-228 (Schmidt, 2015b). Health relevant pathways include inhalation of dust particles with α-decaying radionuclides, ingestion of contaminated soils and plants as well as direct radiation relevant when in close vicinity to tailing materials; or in case of their misuse (e.g. for buildings or road construction).

During rare earth mining and -processing, the radioactive fraction is enriched in the rare earth concentrate (approximately 4- to 20-fold compared to the ore in Bayan Obo (IAEA, 2010)). The radioactive material can pose an issue to humans when the material is not appropriately managed, i.e. when human exposures occur via one or more of the above mentioned pathways. The effective exposure dose is measured in Sievert and based on human body equivalence factors for the different types of radiation (Frischknecht et al., 2000). Health effects include cancer and severe hereditary effects (Frischknecht et al., 2000). If larger groups of individuals are exposed over long time periods, the collective dose as the total sum of all individual exposures is a meaningful indicator for total exposure.

According to the Chinese National Nuclear Safety Administration, naturally occurring radioactive material handled in non-uranium mining activities has become “an urgent problem” (Hua, 2011). Workers at the rare earth mining site can be exposed to elevated radiation levels (IAEA, 2010). During rare earth processing, the gaseous radon contained in the material is released - e.g. during milling. Radon and its decay products are absorbed via inhalation of aerosol particles. Solid radiotoxic material can be inhaled as dust (IAEA, 2010; Schmidt, 2015b). In the case of underground mining, radon concentrations should be carefully managed by ventilation (Schmidt, 2015a). External radiation during processing can be high during specific extraction stages – namely the processing of ores with sulfuric acid, where care has to be taken to avoid direct exposure to extremely high enriched radium sulphate concentrations in the filter stages (Schmidt, 2015a, 2015b). For the general population, the main risk associated with radiation is from inappropriate management of the disposed tailings (Schmidt. 2015b). Long-term storage concepts need to ensure that the release of radioactive substances through various pathways is avoided. Appropriate management according to the latest technical standard consist in covering the radioactive tailings with a combined layer of impermeable clay, sand and pebbles, wet soil and a bio layer. Surface water has to be prevented from entering the disposal cell, which means installing drainages. Special barriers impermissible to radon (clay or clayish material) are required above tailings with an increased uranium content (Schmidt, 2015b). In the past, tailings from rare earth mining in Bayan Obo have been used as building materials or for highway construction (Hua, 2011; IAEA. 2010). This has resulted in elevated radiation levels in homes and in the public, especially for those inhabiting the

buildings (IAEA, 2010). Abandoned and uncovered tailing piles cause additional sources of exposures (Hua, 2011).

The ILCD Handbook gives recommendations for impact assessment choices for life cycle assessment studies conducted in a European context (JRC, 2011). The authors of this document evaluated the method developed by Frischknecht et al., (2000); the only LCIA method developed for the assessment of radiation on human health, and found it to be scientifically robust. The method is also used in Ecoindicator 99, IMPACT 2002, ReCiPe and the Swiss Ecofactor methods. It is based on an exposure model established to model radiotoxic releases in the French nuclear fuel production context. Exposure factors are derived from emission factors and fate models, and converted into DALYs to enable a comparison with other substances toxic to humans. In ReCiPe Version 1.11 (August 2014), characterization factors are expressed in unit DALY/kBq at endpoint and kg U-235/kBq at midpoint. The midpoint indicators are calculated by relating the collective dose of the specific substance to that of the reference substance U-235 (Frischknecht et al., 2000; Goedkoop et al., 2009).

In principle, the damage potential depends on (see e.g. Dreicer et al., 1995):

- the intensity of the radioactive decay (measured in Bq) for both the emitted substances and their decay products,
- the chemo-physical properties of the radioactive material, relevant to its environmental fate,
- the radiation type (α,β,γ) of the emitted radioactive substances and their decay products, relevant to the biological effects,
- the number of people exposed to the radiation, and the duration of the exposure.

At the point of immission to the individual, the “effective dose” is measured in Sievert, a unit which takes into account the differences in types of radiation regarding their potential to affect biological tissues, and the sensitivities of different body tissues (Frischknecht et al., 2000; UNSCEAR, 1993). The collective effective dose, which multiplies the average immission dose (in Sievert) with the number of people affected (expressed in man Sievert), has been recommended as the unit relevant to life cycle assessment by radiation experts (Schmidt, 2015c; Schmidt and Gellermann. 2013). This is in line with the method developed by Frischknecht et al., (2000). Using DALY as the endpoint unit allows for a quantitative comparison of diseases (impaired life years) and deaths (reduced life years) on a single scale, and even the direct quantitative comparison with other impact categories. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) also uses lost life years as an indicator for health effects of exposure to radiation (UNSCEAR, 1993). (This indicator does however not include the life years impaired by a disease as is done with DALYs).

The following issues should be highlighted in the context of life cycle assessment studies on rare earth production:

First, the method developed by Frischknecht et al. (2000)[32] does not currently include any characterization factors for Thorium-232 and its decay product Radium-228. Characterization factors for Uranium-238 and relevant decay products are included. Although the relevance of thorium versus uranium contents differs between deposits, this is relevant, especially if rare earths are mined from deposits with high thorium contents, such as Bayan Obo (see ERECON, 2015). Those nuclides with the highest potential to contribute to the collective dose should be included for a meaningful analysis.

[32] ReCiPe Version 1.11 (August 2014), as implemented in Open LCA Version 1.4.2

Second, the quantification of radiation effects (collective effective dose as specified by UNSCEAR (1993) is for a specific “source” or for a specific “unit of a practice” (UNSCEAR, 1993). As detailed above, one of the main exposure paths is via direct radiation or emission of radon from tailings, if they are not sufficiently and sustainably covered. It should be noted that the effects of both direct radiation and radon emissions from tailings are a function of the surface area of the tailings deposit, rather than the overall mass or volume generated, or rather, the fraction of the surface area which is not provided with an adequate protective cover (Schmidt, 2014). Therefore, they are not proportionally related to the quantities of rare earths mined and processed, as is commonly assumed in life cycle inventories, where particulate and gaseous emissions are given per kg of metal produced.

Generally, life cycle assessment practitioners compile an inventory of emissions and then use an impact assessment model to determine the relative contributions of these emissions with the help of an assessment method. However, the characterization factors provided in the model by Frischknecht are based on a fate model which is valid in a specific context. Previous studies have shown that the human exposure and associated potential damage caused by the releases of radioactive substances or direct radiation from rare earth mining and processing are highly dependent on the management of the radioactive material during mining and processing, and the subsequent management of the radioactive tailings (Schmidt, 2015c; Schmidt and Gellermann, 2013). This is relevant during, as well as long after the rare earth processing activities (Dreicer et al., 1995). Therefore, a determination of emissions in Bq during life cycle inventory compilation would not sufficiently reflect the issue. Consequently, in order to achieve a meaningful analysis for this impact category, site-specific emission and exposure scenarios should be established, and the implications of different management practices on the results discussed (see Schmidt, 2015c). Without these, a meaningful analysis is difficult for this impact category (Schmidt, 2014).

8.3.2 Resource Depletion

One of the benefits of recycling is that it generally means that less primary resources need to be extracted. This is seen as beneficial since the resources remain available for extraction, and can be used for other future purposes. However, there is currently a lack of consensus on how the issue of resource depletion should be addressed in life cycle assessment (Drielsma et al., 2016; LCA Discussion Forum, 2014). A commonly applied method, and the one recommended by JRC for life cycle assessment studies undertaken in a European context, is the abiotic resource depletion method, which uses geological availability as the criterion for the assessment of research extraction (EC -JRC, 2010; Guinée, 1995). Annual extraction rates are compared against the available pool of resources for individual substances (with different reference pools), and compared against a reference substance. However “rare earths are not rare”, i.e. geological availability is not the main issue with rare earth extraction. Rare earths as a group have been classed as critical elements, but the risk of supply disruption varies greatly between the individual elements in this group (EC, 2014; ERECON, 2015; USDOE, 2011). Reasons why potential supply disruptions are discussed for some of the rare earth elements, including neodymium and dysprosium, include low substitutability and geopolitical supply risks. The abiotic resource depletion method does not address criticality, and neither do other ‘traditional’ life cycle impact assessment methods for resource use. A variety of factors is used to classify natural resources in terms of their criticality, all of which either contribute to potential supply risks, or vulnerability to supply disruption on the demand side. Some of these aspects change within short timescales, e.g. when a new technology is successfully brought to market – see e.g. DERA, (2014). Therefore, quantitative assessments of criticality are difficult (Graedel et al., 2015) – but recent efforts are made to develop life cycle impact assessment methods which address criticality.

Furthermore, contrary to emission-based impact categories, resource extraction is sometimes seen as the driver for other associated environmental or social impacts, which, in life cycle assessment, are addressed in separate impact assessment categories. Environmental and social impacts associated with resource extraction are not only seen as a consequence of resource production and/or demand, they are also risk factors considered in criticality assessments, since they could entail supply disruptions, e.g. in the form of potential future environmental legislation. This convoluted configuration can lead to confusion about the issue.

Despite these issues, the category ADP elements was included in the impact assessment, but slightly adjusted to include characterization factors for rare earth elements.

8.4 Conclusion

The research undertaken for this thesis has shown that in addition to its potential role in supply chain diversification, recycling of rare earths from Nd-Fe-B magnets offers environmental impact savings compared to rare earth production from primary deposits. The demand for Nd-Fe-B magnets and the resulting rare earth demand are expected to increase in future, with the potential for new supply shortages being discussed. Due to the growing supply of EOL-magnets, recycling could play an increasingly important role in decreasing the environmental impacts associated with rare earth production, and help address potential supply shortages.

The fact that rare earths occur as a group of elements in the ores entails a joint production situation, which means that the supply mix is largely determined by the composition of rare earths in the ores. However, the demand/ supply ratio is not in balance for individual elements. Prior to the start of this thesis, recycling had been highlighted as a strategy to alleviate this unbalanced market situation (Binnemans et al., 2013b). Hence, a consideration of market effects in the life cycle assessment study was deemed necessary and a consequential life cycle assessment study was conducted. The results show that the magnitude of savings in environmental impacts depends not only on the choice of the processing route, the level of uptake of the recycling practice, but also on market reactions. Due to the joint production situation, reducing the primary production is generally only possible for all joint products as a whole, due to the joint occurrence of REE in the ores. This is true for all processing stages in the REE supply chain whose output is a mix of REE, and largely true for the separation process. A production model was created to illustrate how the introduction of a recycling system would impact the primary production of rare earths, provided the recycling is incentivized by a policy. In particular, the effects on the supply of by-products were investigated. According to these estimates, no supply shortages are to be expected during the considered time period (2020-30) if approximately 20% of “magnet REEs” are provided from secondary sources. It was therefore assumed that the primary production and its associated environmental impacts could be reduced accordingly.

The actual impact the introduction of a recycling system would have is dependent on the choice of the recycling process. Generally, direct recycling processes offer larger environmental impact savings than indirect processing routes since less processing is required (Gauß et al., 2015; Walachowicz et al., 2014). However, it remains to be seen whether a market for direct routes can be successfully established. Indirect routes which extract the rare earths from the magnet material, this is thought to be less of an issue.

The life cycle assessment study for a molten-salt electrolysis recycling process conducted to extract rare earths from Nd-Fe-B magnet material has illustrated a potentially large influence of process parameters not known at early stages of process design. It also showed that there is potential for the recycling process to have a much lower environmental impact than the current primary production routes, and illustrated deficiencies in the current LCI datasets, which remain a subject for further re-

search. In particular, the question regarding the extent of PFC emissions during rare earth electrolysis remains to be answered.

LCA studies undertaken for technical processes which are being developed at lab scale require assumptions for process parameters and process design choices not yet clarified at the earlier stages of research. Furthermore, some important environmental impacts associated with rare earth primary production have not yet been sufficiently addressed in life cycle assessment studies on primary rare earth production, but should be considered in future studies. A detailed comparative life cycle assessment of different recycling processes being developed also remains a task for ongoing research[33].

To date, recycling of REE from Nd-Fe-B magnets has mainly been a topic for research. In recent years, industry players in the Nd-Fe-B magnet supply chain have focused on technical developments which aim to reduce the rare earth content in the magnets, the magnet weight, or avoid the use of Nd-Fe-B magnets altogether. These developments can somewhat discourage the establishment of recycling systems, since

- the supply risk is alleviated by reducing the pressure on the demand side, which can reduce the motivation to invest into recycling for reasons of supply chain diversification, and
- the economic viability of recycling is reduced if the content of the most valuable rare earth metal (dysprosium) is reduced in the magnet material, thereby affecting the value of future scrap (or introducing an uncertainty for potential future recycling companies for longer-term planning).

The demand for Nd-Fe-B magnets in motor applications is increasing, and expected to increase in the near future. In particular, the demand for electric cars is likely to gain momentum in the near future (Spiegel Online, 2017). Consequently, an increasing demand trend for heavy rare earth metals obtained from ion-adsorption clay deposits is plausible, which would entail an increase in EOL-material when the products / components reach the end of their lives, making the establishment of recycling systems for these materials increasingly attractive. Whether rare earth production from secondary sources takes off globally will depend on the development of rare earth prices, on whether Nd-Fe-B recycling will be politically incentivized, and on the perceived geopolitical supply risks outside China, which will themselves be affected by many other factors, including the diplomatic and economic relations between China and other Nd-Fe-B magnet producing countries. In Europe, political incentives are likely necessary to kick-start recycling operations (ERECON, 2015). For some Nd-Fe-B magnet applications, the lack of labelling, and products not designed for recycling represent barriers to cost-effective REE recycling.

[33] Researchers at KU Leuven are currently working on comparative life cycle assessment studies for different rare earth recycling processes from Nd-Fe-B magnets.

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Annex A1 - Supplementary Information for Chapter 4

A.1.1 Quantitative findings – detailed tables

Table 26: REE demand for Nd-Fe-B production, gross demand, including losses in magnet production, tonnes of rare earth metals (in t REM)

		Demand REE for use in different NdFeB application groups, (gross demand incl. losses in magnet production, t REM)							
		2015		2020		2025		2030	
Application group	Unit	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
Electric Two-wheelers	Nd (t)	1600	3740	1860	5360	2150	7690	2500	11070
	Pr (t)	325	765	380	1090	440	1570	510	2260
	Dy (t)	265	445	250	485	225	485	190	410
	Tb (t)	22	37	21	41	19	41	16	34
Air Conditioners	Nd (t)	525	2960	810	4860	1240	7960	1920	13030
	Pr (t)	105	605	165	990	255	1620	390	2660
	Dy (t)	86	290	110	370	130	450	145	485
	Tb (t)	7	24	9	31	11	38	12	40
Traction motors (H)EV	Nd (t)	890	1070	1290	3150	1680	8250	2190	22420
	Pr (t)	180	220	265	645	345	1680	445	4570
	Dy (t)	405	485	345	675	405	1260	470	2180
	Tb (t)	34	41	29	56	34	105	39	185
MRI Scanners	Nd (t)	230	460	150	415	100	375	66	340
	Pr (t)	47	94	31	85	20	77	13	69
	Dy (t)	6	12	4	11	3	10	2	9
	Tb (t)	0	1	0	1	0	1	0	1
Wind Generators	Nd (t)	1490	3250	2110	4600	4090	22000	7910	44410
	Pr (t)	305	665	430	940	835	4490	1610	9060
	Dy (t)	180	385	220	415	370	1390	605	1640
	Tb (t)	15	32	18	35	31	115	51	140
HDD	Nd (t)	1020	1220	950	1310	810	1400	705	1520
	Pr (t)	210	250	195	265	165	285	145	310
	Dy (t)	0	0	0	0	0	0	0	0
	Tb (t)	0	0	0	0	0	0	0	0
Acoustic Transducers	Nd (t)	2030	2030	1840	2360	1660	2730	1500	3170
	Pr (t)	415	415	375	480	340	560	305	645
	Dy (t)	0	0	0	0	0	0	0	0
	Tb (t)	0	0	0	0	0	0	0	0
Magnetic Separators	Nd (t)	970	970	1030	1200	1090	1490	1160	1850
	Pr (t)	200	200	210	245	220	305	235	380
	Dy (t)	105	105	100	100	95	90	89	69
	Tb (t)	9	9	9	9	8	8	7	6
Other Generators	Nd (t)	235	240	240	295	245	355	255	425
	Pr (t)	48	49	49	60	51	72	52	87
	Dy (t)	84	79	79	78	73	75	67	70
	Tb (t)	7	7	7	7	6	6	6	6
Other Motors	Nd (t)	7070	8130	11520	14670	18770	26450	30580	47680
	Pr (t)	1440	1660	2350	2990	3830	5400	6240	9730
	Dy (t)	840	970	1200	1330	1700	1670	2340	1770
	Tb (t)	71	81	100	110	140	140	195	150
Other NdFeB applications	Nd (t)	6740	8160	10090	14790	15110	26780	22600	48440
	Pr (t)	1380	1670	2060	3020	3080	5460	4610	9890
	Dy (t)	1270	1440	1660	2090	2140	2900	2690	3710
	Tb (t)	105	120	140	175	180	245	225	310
Sum	**Nd (t)**	**22810**	**32240**	**31890**	**53010**	**46950**	**105480**	**71370**	**194360**
	Pr (t)	**4650**	**6580**	**6510**	**10820**	**9580**	**21530**	**14570**	**39660**
	Dy (t)	**3240**	**4210**	**3970**	**5560**	**5130**	**8330**	**6600**	**10350**
	Tb (t)	**270**	**355**	**335**	**465**	**430**	**700**	**555**	**865**

Table 27: Supply of Nd-Fe-B material from EOL magnets in years 2015-2030 (t Nd-Fe-B available for recycling, excluding material losses from collection and disassembly)

	Supply NdFeB from EOL appliances from different NdFeB application groups (t NdFeB available for recycling, excluding material losses from collection and disassembly)							
	2015		2020		2025		2030	
Application Group	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
Electric Two-Wheelers	2820	5660	4090	9250	4670	13010	5270	18240
Air Conditioners	490	865	655	1880	890	4320	1330	7480
Traction Motors (H)EV	2	3	70	84	735	955	2480	4310
MRI Scanners	455	540	585	1070	635	1290	425	1020
Wind Generators	8	8	78	85	440	555	1480	2390
Hard disk drives	1330	1480	1520	1730	1240	1550	1030	1550
Acoustic Transducers	1470	1910	1470	1530	1510	1680	1370	1950
Magnetic Separators	1730	1730	1990	1990	2110	2180	2220	2590
Other Generators	32	37	210	235	610	665	905	955
Other Motors	1010	1010	3880	3930	6380	6950	9910	12020
Other NdFeB applications	410	410	525	550	750	920	1100	1620
Sum	**9750**	**13650**	**15070**	**22340**	**19970**	**34070**	**27530**	**54120**

Table 28: Supply of secondary REE from Nd-Fe-B containing EOL appliances in years 2015-2030, excluding losses from collection, disassembly and recycling (in t REM)

		Supply of secondary REE from NdFeB containing EOL appliances, excluding losses from collection, disassembly and recycling (t REM)							
		2015		2020		2025		2030	
Application Group	Unit	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario	Low NdFeB demand scenario	High NdFeB demand scenario
	Nd (t)	580	1170	845	1970	985	2850	1140	4090
	Pr (t)	120	240	175	405	200	580	235	835
	Dy (t)	96	190	135	240	130	255	120	255
Electric Two-Wheelers	Tb (t)	8	16	11	20	11	21	10	21
	Nd (t)	98	170	130	375	180	905	280	1640
Air Conditioners	Pr (t)	20	35	27	77	37	185	57	335
	Dy (t)	21	37	27	76	33	130	40	140
	Tb (t)	2	3	2	6	3	11	3	12
	Nd (t)	0	1	12	14	125	165	440	805
Traction Motors (H)EV	Pr (t)	0	0	2	3	26	34	90	165
	Dy (t)	0	0	5	6	53	66	160	240
	Tb (t)	0	0	0	1	4	6	14	20
	Nd (t)	105	125	135	250	145	300	99	235
MRI Scanners	Pr (t)	21	25	28	51	30	61	20	48
	Dy (t)	3	3	3	6	4	8	3	6
	Tb (t)	0	0	0	1	0	1	0	1
	Nd (t)	2	2	16	18	92	115	315	510
Wind Generators	Pr (t)	0	0	3	4	19	24	64	105
	Dy (t)	0	0	2	3	13	16	42	60
	Tb (t)	0	0	0	0	1	1	4	5
	Nd (t)	310	345	355	400	290	360	240	360
	Pr (t)	63	70	72	82	59	73	49	73
Hard disk drives	Dy (t)	0	0	0	0	0	0	0	0
	Tb (t)	0	0	0	0	0	0	0	0
	Nd (t)	345	450	350	365	355	400	325	460
	Pr (t)	71	92	71	74	73	81	66	94
	Dy (t)	0	0	0	0	0	0	0	0
Acoustic Transducers	Tb (t)	0	0	0	0	0	0	0	0
	Nd (t)	350	350	410	410	450	465	485	570
Magnetic Separators	Pr (t)	72	72	84	84	92	95	99	115
	Dy (t)	64	64	69	69	55	55	48	48
	Tb (t)	5	5	6	6	5	5	4	4
	Nd (t)	6	6	37	41	110	115	160	170
Other Generators	Pr (t)	1	1	8	8	22	24	33	35
	Dy (t)	2	2	14	16	41	44	60	62
	Tb (t)	0	0	1	1	3	4	5	5
	Nd (t)	200	205	790	805	1340	1460	2130	2610
Other Motors	Pr (t)	41	41	160	165	275	300	435	530
	Dy (t)	40	40	140	145	190	200	240	265
	Tb (t)	3	3	12	12	16	17	20	22
	Nd (t)	81	81	105	110	150	190	225	340
Other NdFeB applications	Pr (t)	17	17	21	22	31	38	46	70
	Dy (t)	17	17	22	22	28	32	37	47
	Tb (t)	1	1	2	2	2	3	3	4
	Nd (t)	**2080**	**2900**	**3180**	**4760**	**4230**	**7330**	**5840**	**11800**
Sum	**Pr (t)**	**425**	**595**	**650**	**970**	**865**	**1500**	**1190**	**2410**
	Dy (t)	**245**	**355**	**420**	**585**	**550**	**810**	**750**	**1130**
	Tb (t)	**20**	**30**	**35**	**49**	**46**	**68**	**63**	**94**

A.1.2 Additional information on scenario model assumptions

Table 29: Assumptions HREE content (Dy and Tb) by weight in Nd-Fe-B magnets used in different application groups

	Assumptions weight % HREE of Nd-Fe-B magnets
Electric Two-Wheelers	Low Nd-Fe-B demand scenario: 4% in 2015, reduced to 2% by 2030; high Nd-Fe-B demand scenario: 3% in 2015, 1% by 2030
Air conditioners	Low Nd-Fe-B demand scenario: 5% HREE content until 2015, dropping to 4% by 2015, 2% by 2030; high Nd-Fe-B demand scenario: 5% HREE content until 2015, 2.5% by 2015, dropping to 1% by 2030
(H)EVs	Reduction to 6% by 2020 and 5% by 2030 low demand scenario, 9% -2015 to 5% by 2020 and 2.5% by 2030. (high Nd-Fe-B demand scenario),
MRI Scanners	0,7%
Wind Generators	Low Nd-Fe-B demand scenario: 4% until 2010, 3% by 2015, 2% by 2030. High Nd-Fe-B demand scenario: 4% until 2010, 3% by 2015, 1% by 2030
HDD	0%
Acoustic Transducers	0%
Separators	4 % until 2010, reduced to 3% by 2015 for both scenarios , dropping to 1% in the high Nd-Fe-B demand scenario and 2% in the low demand scenario by 2030
Other generators	8% until 2010, reduced to 6% by 2030 in low demand scenario, 4% in high Nd-Fe-B demand scenario
Other motors	5% in 2005, 4% in 2010, 3% in 2015 for both scenarios, dropping to 2% (low Nd-Fe-B demand scenario) /1% (high Nd-Fe-B demand scenario) by 2030
Others	5% until 2010 for both scenarios,, dropping to 3% by 2030 in the low Nd-Fe-B demand scenario and 2% in the high Nd-Fe-B demand scenario

Table 30: Level of detail available for calculation; and assumptions regarding average magnet weight by application group

	Calculation	Average weight of Nd-Fe-B magnets per appliance
Electric Two-Wheelers	Bottom-up	150g - low Nd-Fe-B demand scenario, 300g - high Nd-Fe-B demand scenario
Air conditioners	Combined approach, based on top-down Nd-Fe-B quantities used for application group for low Nd-Fe-B demand scenario and bottom-up calculation for high Nd-Fe-B demand scenario	For the low Nd-Fe-B demand scenario, estimates from Constantinides are applied. For the high Nd-Fe-B demand scenario, 250g/appliance for residential air conditioners is assumed
(H)EVs	Bottom-up	2.1 kg BEV, PHEV, FCEV; 1.4 kg hybrid cars, weight reduced to 80% in low Nd-Fe-B demand scenario
MRI Scanners	Combined approach based on number of low field scanners and average magnet weight for scanner for earlier years, and percentage of magnets used for application group in 2010/2015	1500kg/ MRI scanner
Wind Generators	Bottom-up	Low-speed direct drive PM generators: 600kg/MW until 2014, 550kg/MW by 2020, 500kg/MW by 2030; mid-speed PM generators: 160kg/MW, dropping to 130 kg/MW by 2030
HDD	Bottom-up	2.5g/4g for 2.5" drives (low and high Nd-Fe-B demand scenario), 14g in 2011 for 3.5" drives, dropping to 8.8 g by 2030
Acoustic Transducers	Based on Nd-Fe-B quantities used for application group	N/A
Separators	Based on top-down Nd-Fe-B quantities used for application group	N/A
Other generators	Based on top-down Nd-Fe-B quantities used for application group	N/A
Other motors	Based on top-down Nd-Fe-B quantities used for application group	250g/car, different for other motor applications in this category
Others	Based on Nd-Fe-B quantities used for application group	N/A

A.1.3 Scenario assumptions – details by application group

A.1.3.1 Assumptions for electric two-wheelers

Data from various sources was combined to construct a low and a high demand scenario for Nd-Fe-B magnets used in electric two-wheelers. E-bicycles, scooters and e-motorbikes are included. The figures are based on estimates for annual sales quantities found in the literature. For the low Nd-Fe-B demand scenario, a 2.8 % growth rate is assumed from 2015 for electric bicycle numbers. For the high Nd-Fe-B demand scenario, a 7.5% annual growth rate is assumed from 2018 - 2030, with literature estimates used for years 2012-18 (Fu, 2013; INSG, 2014), and interpolated for years in between. It was assumed that 100% of electric two-wheelers produced today use sintered Nd-Fe-B magnets in their motors in the time period considered. With the slower growing e-motorbike and scooter estimates included (1-2% annual growth in number of vehicles), this results in an annual demand growth for Nd-

Fe-B used in electric two-wheelers of around 3% for the low Nd-Fe-B demand scenario (from 2016) and around 7% (from 2019) for the high Nd-Fe-B demand scenario.

Values for magnet weights of Nd-Fe-B magnets in 2-wheel electric drive motors are between 0.06 and 0.35kg (Bast et al., 2015; Habib and Wenzel, 2014; Harris, 2012; Hoenderdaal et al., 2013; Shaw and Constantinides, 2012; Zepf, 2013) and the dysprosium content of those magnets is estimated at 4% (Binnemans et al., 2013a; Hoenderdaal et al., 2013). 150g magnet weight per electric two-wheeler is assumed for the low Nd-Fe-B demand scenario, and 300g for the high Nd-Fe-B demand scenario.

For the low Nd-Fe-B demand scenario, a HREE content of 4% was assumed for 2015, which is reduced to 2% until 2030. For the high Nd-Fe-B demand scenario, a HREE content of 3% in 2015, reduced to 1% by 2030, was assumed. The Nd content was calculated accordingly (total REE content 31% by mass in Nd-Fe-B assumed).

Habib and Wenzel (2014) assume a 10-year lifetime for electric two-wheelers. Zeit Online (2013) estimate a 4-year lifetime for e-bikes (electric two-wheelers) in China. The typical Chinese e-bike is significantly cheaper than the e-bikes sold on the European market (Fu, 2013). Since China dominates the market for e-bikes, a 5-year lifetime with a standard deviation of 1.25 years is assumed.

An 80% collection rate for EOL e-bikes and a 90% efficiency rate during disassembly were assumed.

A.1.3.2 Assumptions for air conditioners

Difficulties in applying a bottom-up approach for Nd-Fe-B use in air conditioners arise from a lack of information on the market share of Nd-Fe-B magnets and the large variation in magnet weights per air conditioning unit. Therefore, Nd-Fe-B use in air conditioners was estimated as follows:

For the low Nd-Fe-B demand scenario, the figures provided by Constantinides (2012) - ca. 1245t in 2010 were used, and the general growth rate of 8.5% predicted for air conditioners for years 2010-30 was applied (PR Newswire, 2015c). A growth rate of 3% was assumed for years 2000 to 2009.

For the high Nd-Fe-B demand scenario, 2009 and 2012 global residential air conditioner units with inverter technology (Daikin Global, 2015) are used as a basis for the scenario calculation, assuming those figures can be used as an indication for the market size of Nd-Fe-B-based air conditioner compressor motors. The numbers are combined with average magnet weights. Average magnet weights for residential air conditioners are derived from a forecast for Nd-Fe-B demand for air conditioners in China, and the forecast unit sales (Daikin Global, 2015; Frontier Rare Earths, 2012; Research in China, 2011). This yields a 250g magnet weight per unit. Those figures are similar to other typical magnet weights reported in the literature for residential air conditioners (Seo and Morimoto, 2014). A 10% growth rate, i.e. a larger than average growth rate, was assumed for efficient air conditioner motors, used in more energy efficient air conditioning systems was assumed for years 2013-2030 (PR Newswire, 2015a; Yu, 2014). A growth rate of 10% was assumed for years 2000 to 2008.

Estimates for Nd-Fe-B use in industrial air conditioners are not included in our estimates, due to lack of information.

The dysprosium content for Nd-Fe-B magnets used in air conditioner is given at around 5 (3-7) weight % in the literature (Mikami, 2012; Seo and Morimoto, 2014), and is expected to drop to 2.5-3% by 2015 (Seo and Morimoto, 2014). A current 4% of HREE content are assumed for the low Nd-Fe-B demand scenario, dropping to 2% by 2030 and 2.5% for the high Nd-Fe-B demand scenario, dropping to 1% by 2030.

Seo and Morimoto (2014), estimate a 12.7-year lifetime for air conditioners. Habib et al. (2014) estimate 10 years. A lifetime of 12 years for air conditioners and a standard deviation of 3 years were assumed.

The collection and recycling of magnets from air conditioners is already being practiced in Japan (Hitachi Ltd., 2010; Mitsubishi Electric, 2014b). A 60% collection rate and 90% efficiency during disassembly were assumed. Estimates for air conditioner collection rates in different countries are given in KPMG (2014). This estimate is higher due to the future perspective of this study.

A.1.3.3 Assumptions for traction motors of hybrid and electric cars ((H)EV)

Historic sales figures for hybrid and electric vehicles were compiled from a variety of sources (BBC Research, 2015; EVI, 2015; Kühn et al., 2014; Navigant Research, 2015), including hybrid, plug-in hybrid, and full electric vehicles. Estimates for fuel cell electric vehicle sales are adopted from Kühn et al. (2014). According to Navigant Research (2015), approximately 6.4 million electric vehicles sales are expected for 2023, up from 2.7 million in 2014, which corresponds to an approximate annual growth rate of 10%. Assume 5% growth rate was assumed from 2014 until 2030 for the pessimistic scenario and a 20% annual growth rate for the optimistic scenario, in numbers of vehicle sales.

Values for magnet weights of Nd-Fe-B magnets in hybrid and electric vehicle drive motors found in the literature are between 1 and 2.4 kg (Bast et al., 2015; Hoenderdaal et al., 2013; Johnson, 2014). According to Zepf (2013) citing Gutfleisch et al. (2011), Toyota reported a 1.3kg magnet weight for the drive motors in their hybrid cars in 2003. Bast et al. (2015) assume 2.1 kg of magnet for BEV, PHEV and fuel cell (FCEV) vehicle motors (80kW) and 1.4 kg of magnet for motors used in hybrid cars (20kW). The assumptions from Bast (2015) were adopted.

Furthermore, Bast et al. (2015) assume that 25% of electric vehicles and 100% of plug-in and hybrid electric vehicles use permanent magnet motors. According to ZSW (2015), the most popular BEV model is the Nissan Leaf, which uses permanent magnet motors. In 2014, Nissan Leaf registrations (indication for sale quantities) are around 57,000, around 31% of global BEV production (EVI, 2015; ZSW, 2015). In absence of any more detailed information, 25% of electric vehicles /fuel cell electric vehicles were assumed to use permanent magnets for the low Nd-Fe-B demand scenario and 75% for the high Nd-Fe-B demand scenario.

Traction motors used in hybrid and electric cars are amongst the applications with the highest requirements for heavy REEs, due to the high operating temperatures. Figures reported in the literature for the dysprosium content in these magnets range from 3.6 to 12 magnet weight % (Bast et al., 2015; Binnemans et al., 2013a; Constantinides, 2014b, 2014b; Gutfleisch et al., 2011; Hoenderdaal et al., 2013; Rademaker et al., 2013). Rotor magnets from traction drives analyzed in the MORE project (see Chapter 6.5.2) contained 8-12 weight % Dy (Bast et al., 2015). Constantinides (2014a) estimate that a reduction to 6 weight % Dy will be possible for magnets used in traction drives of hybrid and electric vehicles. An estimate provided by a German manufacturer assumes a reduction to 5% Dy by 2020, with a reduction to 2.5% feasible in future (Schüler et al., 2015).

A total REE content of 31% by weight in the magnets was assumed.

For the high Nd-Fe-B demand scenario, a stronger HREE reduction from 9% of magnet weight in 2015 to 5% by 2020 and 2.5% by 2030 was assumed. For the low Nd-Fe-B demand scenario, a reduction to 6% by 2020 and 5% by 2030 was assumed.

Figures for average passenger vehicle lifetimes often cited in the literature range between 10 and 15 years (Bast et al., 2015; Busch et al., 2014; Habib and Wenzel, 2014; Hoenderdaal et al., 2013; Seo

and Morimoto, 2014), but can be twice as long in developing countries (Harraz and Galal, 2011). In Europe, Japan, China and Korea, End-of-life (EOL) vehicle legislation is in place which specifies recycling and recovery rates for EOL vehicles (EU, 2000; Sakai et al., 2014). This is a good precondition for the recycling of Nd-Fe-B magnets from vehicles, since the collection and disassembly systems are already in place.

In the EU, the EOL vehicle directive requires an 85% recycling/reuse rate for end of life vehicles in Europe from 2015, and a 95% recovery rate. Similar targets exist in Japan and Korea. Figures reported by EU member states on 2011 implementation show recycling rates between 77% and 93%. These figures, however, do not provide information about collection rates / cars exported for reuse.

A lifetime of 15 years was assumed to account for the extension of the lifetime via reuse and a normal distribution applied (with a standard deviation of 3.75 years). Furthermore, a 90% collection rate was assumed, with the rest of the cars not collected for recycling, and a 90% efficiency of disassembly.

A.1.3.4 Assumptions for MRI scanners

Little information on Nd-Fe-B magnet use in MRI scanners was available in the literature. A combined bottom-up and top-down approach is used due to lack of reliable data.

Percentages on the share of global Nd-Fe-B magnet use in different application groups provided by Constantinides (2012) for years 2010 and 2015 were used to construct the high Nd-Fe-B demand scenario. The numbers indicate a declining trend for the use of Nd-Fe-B magnets in MRI scanners. According to Zepf (2015), the global demand figures for Nd-Fe-B used in MRI scanners should be lower than estimated by Constantinides, but he does not provide a global estimate. 50% of the 2010 and 2015 quantities provided by Constantinides were assumed for the low Nd-Fe-B demand scenario, and a 8%/2% annual decline from 2015 to 2030.

Cosmus and Parizh (2011) state that approximately 600 low-field MRI scanners were produced in 2000 and the production was almost stopped in 2005. 200 low-field MRI scanners were assumed for 2005 and the numbers taken as an estimate for MRI scanners using Nd-Fe-B magnets. No information was available for other years. Since PM-based MRI scanners have been on the market since 1990 at least (Sasaki et al., 1990), 100 MRI scanners were estimated to have been put on the market in that year.

Values for magnet weights of Nd-Fe-B magnets in MRI scanners are between 700 and 3000 kg per device (Bast et al., 2015; Talens Peiró et al., 2013). A magnet weight of 1500kg Nd-Fe-B per MRI scanner was assumed for this study. Information on the dysprosium content in MRI scanners found in the literature is between 0 and 1.4% (Binnemans et al., 2013a; Mikami, 2012). 0.7% of HREE by weight and an overall 31% of REE by mass, i.e. 30.3% LREE content by mass were assumed.

In the high Nd-Fe-B demand scenario, the global production levels for Nd-Fe-B magnets used in MRI scanners were assumed to decline by 2% over the next 15 years. In the low Nd-Fe-B demand scenario, an annual 8% decline from 2015 until 2030 was assumed.

Assumption EOL supply:

Collection rates for MRI scanners were assumed to be 80%, with 90% efficiency during disassembly.

Du and Graedel (2011) assume a 10-year lifetime for MRI scanners. They quote a blog which mentions that the scanners are used for 12-14 years in most cases (Keefer). Furthermore, MRI manufacturers offer refurbished MRI scanners, see e.g. (Hitachi, 2015d; Philips, 2015; Siemens, 2015). Therefore, a lifetime of 12 years was assumed, normally distributed with a standard deviation of 3 years.

A.1.3.5 Assumptions for generators used in wind turbines

Figures for annual global wind turbine installations and forecasts are compiled from GWEC and JRC (GWEC, 2015; Lacal-Arántegui and Serrano-Gonzales, 2015). Since the GWEC projection ends in 2019, an annual growth rate of 15% was assumed for direct drive turbines (in MW installed) to construct the low Nd-Fe-B demand scenario. The JRC projection forms the basis for the high Nd-Fe-B demand scenario.

The share of direct drive, permanent magnet generators was then estimated based on various figures found in the literature. According to JRC, gearless direct drive turbines are commonly installed in Asia and becoming more popular there, whereas permanent magnet generators in Europe are mainly used in geared, mid-speed turbines (Lacal-Arántegui and Serrano-Gonzales, 2015). Estimates in the literature for the permanent magnet direct drive market share by 2020 are between 10 and 40%, and 5-30% for 2030 (Buchert, 2011; Hoenderdaal et al., 2013; Moss et al., 2011; Oakdene Hollins, 2010; Zepf, 2013). Permanent magnet generators (PMG) constitute one of the technologies with potential for higher performance (Lacal-Arántegui, 2015), which points towards an increased use of the technology. China has become the biggest market for new wind turbine installations (GWEC, 2015) and the country to produce most sintered Nd-Fe-B magnets (Kingsnorth, 2014b). They were therefore assumed to continue expanding the use of PMG due to the facility of access to REEs and REPM. A total 122 GW of PM DD turbines installed in 2003, 4105 GW in 2010, and a 15-30 % market share of new installations by 2030 are assumed.

Assumptions for Nd-Fe-B magnet weights per MW in direct drive, low speed permanent magnet generators center around 500-700 kg/MW (Buchert, 2011; Lacal-Arántegui et al., 2013; Moss et al., 2013). 600kg were assumed until 2014. Target specifications for magnets used in wind turbines aim at an improvement in magnet power density (kJ/m3) by around 20% between 2014 and 2020 and by another 15% between 2020 and 2030 (Lacal-Arántegui, 2015), implying a corresponding weight reduction around the same magnitude. However, the values are communicated as ambitious and hard to achieve. On this basis, a smaller reduction to 550kg/MW by 2020 and 500 kg/MW by 2030 for DD low speed turbines were assumed.

For medium speed generators, annual installation figures are estimates based on Lacal- Arántegui et al. (2015) and GWEC (2015), around 8% of installed power in 2012. 8% by 2030 were assumed for the low Nd-Fe-B scenario and 17% for the high Nd-Fe-B demand scenario. Magnet weights in medium and high speed generators were assumed at 160kg/MW (Lacal-Arántegui et al., 2013). The magnet weight was assumed to drop to 130kg/MW by 2030.

Assumptions for HREE content in wind turbines, low Nd-Fe-B demand scenario: 4% until 2010, 3% by 2015, 2% by 2030. High Nd-Fe-B demand scenario: 4% until 2010, 3% by 2015, 1% by 2030.

Recycling potentials:

The wind turbines were assumed to be in use for 22 years to account for some reinstallations, and a normal distribution a standard deviation of 5.5 years were applied. 10% of the magnet material is assumed to be lost during collection and 10% during disassembly, respectively.

A.1.3.6 Assumptions for hard disk drives

Nd-Fe-B demand for voice coil motors in hard disk drives (HDD) has been calculated from shipments, average magnet weights and REE contents. Scenario assumptions were directly adopted from Sprecher (2014a) for the years considered in the paper (until 2017). The figures were modified as follows:

For the demand calculations, the projection was extended until 2030, based on the following assumptions: Shipment figures were adopted from Forbes projection (years 2018 & 19). The following assumptions were made for shipments in years 2019-2030:

- 5% increase for enterprise applications per year (high Nd-Fe-B demand scenario)
- 0% increase for enterprise applications per year (low Nd-Fe-B demand scenario)
- 5% decrease for consumer applications per year (low Nd-Fe-B demand scenario)
- 0% decrease for consumer applications per year (high Nd-Fe-B demand scenario)

Shipments were adjusted to include HDD for “branded products”, external storage devices for private and small office use and media players, based on Forbes data for years 2011-2019. Branded products are assumed to be of 2.5” size. 0% increase for low Nd-Fe-B demand scenario, 2% increase for high Nd-Fe-B demand scenario for years 2019-2030 is assumed.

- Weight of magnet in 2.5” drives: 2.5g for low Nd-Fe-B demand scenario, based on (Sprecher et al., 2014a), 4g for high Nd-Fe-B demand scenario (Sheridan, 2015).
- Weight of magnet in 3.5” drives adopted from Sprecher, 14g reduced to 8.8g by 2017, no change assumed after 2017.
- Assumption: 0% HREE

Calculations: supply from EOL

Lifetime assumptions are between 5 and 10 years in the literature (Binnemans et al., 2013a; Habib and Wenzel, 2014). The lifetime and recycling and disassembly process efficiencies were adopted from Sprecher (2014a), who assume 6 years for portable consumer applications, 10 years for desktops, 6-years for enterprise applications. A 6-year lifetime is assumed for branded products, normally distributed with a standard deviation of 1.5 years.

A 60% overall collection rate is assumed - collection rates for HDDs in enterprise applications are likely to be higher than for consumer applications. The collection percentage for consumer applications is around 50% for consumer applications of HDD (Bast et al., 2015), which dominate in numbers during the time frame considered. Sprecher (2014a) take only losses during disassembly into account.

Sprecher (2014a) assume a 65% loss during disassembly for HDD in consumer equipment, based on disassembly trials in the Netherlands but expect losses to be lower for enterprise HDDs. An overall 40% loss during disassembly was assumed. A 90% material efficiency for the direct recycling process assumed for HDDs based on Sprecher (2014a), which is in line with the analysis conducted here(12% material loss; calculations from EREAN project)

A.1.3.7 Assumptions for acoustic transducers

The Nd-Fe-B demand figures for acoustic transducers from Constantinides (2012) are adopted for years 2010 and 2015 and numbers interpolated for the years in between. For years 2005-2010, it is assumed that 12-16% (low and high Nd-Fe-B demand scenario) of the global Nd-Fe-B demand was for acoustic transducer applications (i.e. the assumption made here is lower than the 25% estimate by Du and Graedel (2011). Based on the trend indicated by Constantinides (2012), the general expectance of slow growth in Nd-Fe-B use for these applications (Hoenderdaal et al., 2013; Lucas et al., 2015), and in light of the uncertainties regarding the market share of the more recently developed piezoelectric

speakers, a 2% annual decline in Nd-Fe-B use for the low Nd-Fe-B demand scenario, and a 3% increase for the high Nd-Fe-B demand scenario are assumed for years 2015-30.

Assuming mobile phone speakers and notebook speakers all use Nd-Fe-B magnets, and based on the weights of magnets used in these speakers reported in the literature (Buchert et al., 2012; Zepf, 2013), around 9% of Nd-Fe-B magnets used for transducer applications are used in mobile phone speakers and 20% in notebook and tablet speakers. Detailed information on the breakdown of other Nd-Fe-B transducer applications was not available. Whilst the magnets in mobile phone speakers require disproportionately high disassembly efforts, magnets from larger speakers could be an attractive source for secondary REEs.

Zero HREE content in acoustic transducers as reported in Binnemans et al. (2013a), and a 31% Nd content by mass are assumed. Du and Graedel (2011) estimate a 10-year lifetime for Nd-Fe-B magnets in audio systems. Lifetimes for mobile phones, tablets and notebooks are likely to be much shorter; however, assuming that higher recycling rates are achievable for applications with higher magnet weights, appliances with longer lifetimes are more relevant. An 8-year lifetime with a standard deviation of 2 years, with average collection rates of 50%, and 50% losses during disassembly are assumed (it is unlikely that very small magnets from mobile phones etc. will be extracted due to the very low weights).

A.1.3.8 Assumptions for magnetic separators

Very little information about production quantities for magnetic separators was found in the literature. They are, however, treated as a separate category, due to the potentially large magnet weights per separator, and the potential to set up business-to business recycling schemes, which makes them a potentially attractive source of secondary material. The estimates for Nd-Fe-B magnets used in magnetic separators in years 2010 and 2015 given by Constantinides (2012) are used as a basis for our calculation. A 1% growth rate of Nd-Fe-B demand is assumed for the low Nd-Fe-B demand scenario, and a 4% growth for the high Nd-Fe-B demand scenario.

Warranties for magnetic separators are typically given for one year; however, the machines are in use for longer in practice. According to one manufacturer, the machines are normally serviced after 5 or 10 years in use, and the magnets then often need to be replaced. A second manufacturer estimates a 12-year lifetime. A lifetime of 10 years with a standard deviation of 2.5 years was assumed. Binnemans et al. (2013a) assume a 2.8% Dy content for magnetic separators, Constantinides (2012) assumes 4%. A 4.4% HREE content until 2010 was assumed for this study, reduced to 2.8% by 2015, dropping to 1% in the high Nd-Fe-B demand scenario and to 2% in the low Nd-Fe-B demand scenario by 2030. The Nd content is derived accordingly, with a total REE content of 31% assumed. A high collection rate (80%) is deemed feasible and an 80% efficiency during disassembly.

A.1.3.9 Assumptions for “Other generators” (excl. wind turbine generators)

Detailed information on the market for Nd-Fe-B-based generators could not be found in the literature. The percentages provided by Constantinides (2012) are used as a starting point for the calculation for years 2010 and 2015, with values interpolated for years 2011-14. For years 2005-2010, 1% growth is assumed for the high Nd-Fe-B demand scenario, 5% for the low Nd-Fe-B demand scenario. 0% growth is assumed for the low Nd-Fe-B demand scenario, and 3% growth for the high Nd-Fe-B demand scenario from 2015 onwards.

Values for the dysprosium content for Nd-Fe-B magnets used in generators range between 6.4% and 9% (Binnemans et al., 2013a; Constantinides, 2012). 8% HREE content was assumed until 2010, re-

ducing to 4% in the high Nd-Fe-B demand scenario and to 6% in the low Nd-Fe-B demand scenario by 2030.

Generator lifetimes are between 20 and 30 years for larger generators (Hydroworld, 2010; Kramer et al., 2012; Siemens, 2014a), but likely to be shorter for smaller generators used in cars and bikes. In absence of any more detailed information on the shares of different generator applications, an average lifetime of 20 years with a standard deviation of 5 years was assumed. Collection and disassembly efficiencies are assumed at 80% and 90%, respectively.

A.1.3.10 Assumptions for “Other motors”

Figures on the share of Nd-Fe-B-based motors are difficult to obtain for individual motors applications due to diversity of the Nd-Fe-B motor applications summarized in this group. This makes a detailed bottom-up analysis very difficult. Therefore, the scenario assumptions will be based on the figures provided by Constantinides (2014b).

There is a global trend towards more efficient motors in industrial and commercial applications, which is expected to drive the demand for Nd-Fe-B-based motors. The use of Nd-Fe-B magnets for motors is predicted to grow at an annual rate of 10.8% (DrivesNControls, 2015). (This includes all types of Nd-Fe-B-based PM motors, including those covered in separate categories in this paper.) Constantinides (2014b) assume an average growth rate of 9% for motors in group “other motors” between years 2010 and 2015, with around 25% of Nd-Fe-B magnets overall used in these motor applications.

In order to estimate demand growth, recycling rates and product lifetimes, it is desirable to obtain an estimate for the use of Nd-Fe-B in different motor applications in group “other motors”. According to PR Newswire (2015b), factory automation is the largest market by value for PM motors. However, when calculating the demand for Nd-Fe-B in small automotive motors, based on vehicle sales and the estimated 250g Nd-Fe-B/car (Shaw and Constantinides, 2012), Nd-Fe-B demand figures for this application of approximately 80% of the quantities provided by Constantinides are obtained for all motor applications summarized in this group. The 250g include magnets in sensors (and generators), so a smaller average weight assumption for Nd-Fe-B magnets used in automotive motors may be appropriate to avoid double-counting of the magnets in different categories. Furthermore, there is a general trend towards electrification and the replacement of ferrite motors with bonded Nd-Fe-B motors, a decreasing factor to the overall weight of sintered magnets used in small motors in cars. It is possible that the 2015 figures provided by Constantinides (2012) for category “other motors” should be corrected upwards.

For the low Nd-Fe-B demand scenario, the figures provided by Constantinides for years 2010 and 2015 are adopted, and an annual growth rate of 10% is assumed for years 2015-30. For the high Nd-Fe-B demand scenario, the 2010 figure provided by Constantinides is adopted, and a 12% growth rate assumed for years 2010-2030.

Binnemans et al. (2013a) estimate a 4% dysprosium content for magnets in small automotive, industrial and other applications, a few years back, Constantinides (2012) estimated 6%. Hoenderdaal et al. (2013) estimate 3% for industrial motors. Around 2 to 3% dysprosium are used in pumps (Anonymous, 2015f). Due to the ongoing HREE reduction efforts, the average dysprosium content is likely to decrease until 2030. For example, Nd-Fe-B magnets used in EPS motors are available without dysprosium (Anonymous, 2015c); Dy-free compression-molded magnets are used in seat motors (Honkura, 2013). A 5% HREE content by weight in 2005 is assumed, dropping to 4% in 2010 and 3% in 2015. For the low Nd-Fe-B demand scenario, a HREE content reduction to 2% by 2030 is assumed, and a reduction to 1% for the high Nd-Fe-B demand scenario.

Lifetimes for motors used in cars can be derived from lifetimes for cars which are around 10-15 years, with nearly twice the lifetime in some developing countries (Harraz and Galal, 2011). Lifetimes for motors in industrial applications in Germany are around 10-15 years for most synchronous motors (60%), with shorter lifetimes for 10% and longer lifetimes for 30% of motors – but exports of industrial plants to countries outside Europe for reuse are common practice (Buchert et al., 2013). The figures refer to the first lifetime of the motors; some resales of machines are happening. The recommended lifetime for circulation pumps is 10 years for energy efficiency considerations, but the pumps are often in use for 20 or 30 years in practice (Anonymous, 2015f). A lifetime of 13 years is assumed for motors in the broad category of “other motors” (standard deviation of 3.25 years).

Collection rates for REPM motor applications of 80% are estimated, with disassembly efficiency of 40%. It is likely that achievable disassembly efficiency rates will tend to be higher than 40% for larger magnets and unlikely that the extraction of small magnets from auxiliary motors will be economically viable in the near future. The magnets can be very small, e.g. 16g of a bonded Nd-Fe-B magnet in a 235g seat motor (Honkura, 2013). The disassembly efficiency will depend on the fraction of motors which reaches disassemblers that extract Nd-Fe-B magnets from motors – the overall efficiency could be lower if disassemblers which only focus on other metal fractions collect most REPM motors and the magnets enter the steel scrap recycling stream.

A.1.3.11 Assumptions for other Nd-Fe-B magnet applications

Nd-Fe-B demand quantities provided by Constantinides (2012) for 2010 are used as a basis. A ten-year lifetime with a standard deviation of 2.5 years is assumed. Average annual growth rates of 4% until 2010 are assumed for the low and high Nd-Fe-B demand scenarios, 8% after 2010 for the low demand scenario, and 12% after 2010 for the high demand scenario. An average HREE content of 5% was assumed until 2010, dropping to 3% by 2030 in the low demand scenario and 2% in the high demand scenario. A collection rate of 30% and a 10% efficiency of disassembly were assumed.

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Annex A2 – Supplementary Information for Chapter 5

Results per 1t of REO concentrate after leaching, at 91% purity - low estimate, leachate reuse scenario: **9 t CO_2 equ.**
Results per 1t REO; separated after SX - low estimate, leachate reuse scenario: **31 t CO_2 equ.**

Table 31: Contribution analysis, percentage of GWP 100a (%), low estimate with leachate reuse scenario (per metric ton of separated REO after SX)

Contribution %			Process
100			production of individually separated REO from ion-adsorption clays, after SX, low estimate (LEACHATE REUSE SCENARIO)
	33		production of RE concentrate 91%, ion-adsorption clays, low estimate , LEACHATE REUSE SCENARIO
			production of RE concentrate 91%, ion-adsorption clays, low estimate , LEACHATE REUSE SCENARIO
		14	market for ammonium bicarbonate | ammonium bicarbonate | APOS, U - GLO
		8	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
		3	market for ammonium sulfate, as N | ammonium sulfate, as N | APOS, U - GLO
		2	market for excavation, hydraulic digger | excavation, hydraulic digger | APOS, U - GLO
		2	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
		1	market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, U - GLO
		0.7	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised | APOS, U - GLO
		0.2	market for sulfuric acid | sulfuric acid | APOS, U - GLO
		0.0	market for limestone, crushed, for mill | limestone, crushed, for mill | APOS, U - GLO
	18		market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
	16		market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | APOS, U - RoW
	14		market for citric acid | citric acid | APOS, U - GLO
	10		market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U - GLO
	6		heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
	0.2		water production, deionised, from tap water, at user | water, deionised, from tap water, at user | APOS, U - RoW
	0.0		p204
	0.0		clinker production | spent solvent mixture | APOS. U - RoW
	6		direct CO_2 emissions
	100		

Results per 1t of REO concentrate after leaching, at 91% purity - low estimate: **11 t CO_2 equ.**
Results per 1t REO; separated after SX - low estimate: **33 t CO_2 equ.**

Table 32: Contribution analysis, percentage of GWP 100a (%), low estimate scenario (per metric ton of separated REO after SX)

Contribution (%)			Process
100			production of individually separated REO from ion-adsorption clays, after SX, low estimate
	37		production of RE concentrate 91%, ion-adsorption clays, low estimate
		13	market for ammonium bicarbonate | ammonium bicarbonate | APOS, U - GLO
		8	market for ammonium sulfate, as N | ammonium sulfate, as N | APOS, U - GLO
		7	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
		2	market for excavation, hydraulic digger | excavation, hydraulic digger | APOS, U - GLO
		2	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
		1	market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, U - GLO
		0.6	market for polyvinylchloride, suspension polymerised | polyvinylchloride, suspension polymerised | APOS, U - GLO
		0.2	market for sulfuric acid | sulfuric acid | APOS, U – GLO
		0.0	market for limestone, crushed, for mill | limestone, crushed, for mill | APOS, U - GLO
	17		market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
	15		market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | APOS, U - RoW
	13		market for citric acid | citric acid | APOS, U – GLO
	9		market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U - GLO
	5		heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
	0.2		water production, deionized, from tap water, at user | water, deionized, from tap water, at user | APOS, U - RoW
	0		P204
	0		clinker production | spent solvent mixture | APOS, U – RoW
	5		direct CO_2 emissions
	100		

Results per 1t of REO concentrate after leaching, at 91% purity –high estimate: **20 t CO_2 equ**

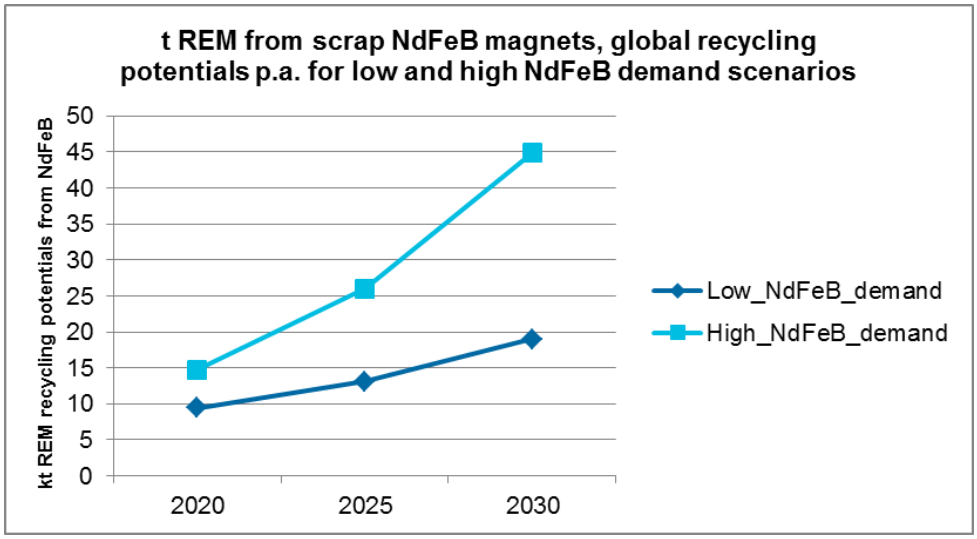
Results per 1t REO, separated after SX - High estimate: **53 t CO_2 equ**

Table 33: Contribution analysis, percentage of GWP 100a (%), high estimate scenario (per metric ton of separated REO after SX)

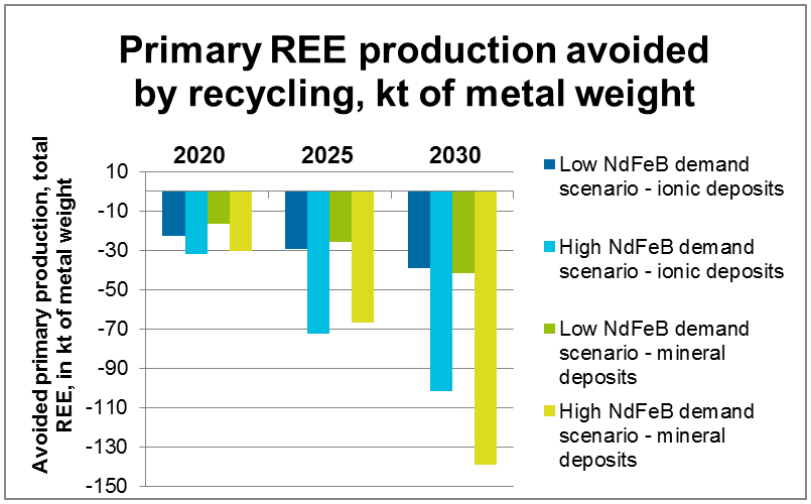
Contribution (%)			Process
100			production of individually separated REO from ion-adsorption clays, after SX, high estimate
	42		production of RE concentrate 91%, ion-adsorption clays, high estimate
		13	market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
		11	market for ammonium bicarbonate | ammonium bicarbonate | APOS, U - GLO
		8	market for ammonium sulfate, as N | ammonium sulfate, as N | APOS, U - GLO
		6	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
		1	market for excavation, hydraulic digger | excavation, hydraulic digger | APOS, U - GLO
		0.4	market for polyvinylchloride, suspension polymerized | polyvinylchloride, suspension polymerized | APOS, U - GLO
		0.3	market for sulfuric acid | sulfuric acid | APOS, U - GLO
		0.1	market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, U - GLO
22			market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U - GLO
11			market group for electricity, medium voltage | electricity, medium voltage | APOS, U - CN
10			market for citric acid | citric acid | APOS, U - GLO
10			market for hydrochloric acid, without water, in 30% solution state | hydrochloric acid, without water, in 30% solution state | APOS, U - RoW
3			heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, U - RoW
0.5			p204
0.3			water production, deionized, from tap water, at user | water, deionized, from tap water, at user | APOS, U - RoW
0.0			clinker production | spent solvent mixture | APOS, U - RoW
	6		direct CO_2 emissions
	100		

Annex A3 – Supplementary Information for Chapter 6

A.3.1 Data (Tables and Figures)



A3 - Figure 1: Recycling potentials (potential for secondary REE production) for each reported year from industrial and EOL scrap magnet (kt "magnet REM" (sum of Nd, Pr, Dy and Tb in metal weights)



A3 - Figure 2: Avoided REE production by production route and by Nd-Fe-B demand scenario (t "REE" in metal weights, total avoided primary production, La ~Lu & Y)

Table 34: REE content in various ion-adsorption clay deposits (t REM/ t REM), compiled from (EC 2014; Gupta and Krishnamurthy, 2005; Packey, 2016a; Papangelakis, 2014; Schüler et al,. 2011)[34]

	Ion-adsorption clay deposits						Mineral deposits (Bayan Obo composition)	
REE	**A) Ion-adsorption type ore - Longnan**	**B) Ion-adsorp-tion type ore. Xunwu 1**	**C) Ion-adsorp-tion type ore. Xunwu 2**	**D) Ion-adsorption type ore. "location unspeci-fied"**	**E) „B1"**	**F) „B2"**	**Typical LREE-rich mineral deposits, Bayan Obo com-position**	**G) Average across 51 deposits. incl. hard rock. LREE dominant deposits**
	Average from differ-ent sources ((Gupta and Krishnamurthy. 2005; Krishnamurthy and Gupta. 2016; Schüler et al., 2011)	**(Gupta and Krishna-murthy. 2005)**	**(Schüler et al., 2011)**	**(Packey. 2016a)**	**(Papange-lakis. 2014)**	**(Papange-lakis. 2014)**	**(Packey. 2016a). (Gupta and Krishnamurthy. 2005))**	**(EC. 2014))**
Lanthanum	1.9%	42.4%	29.8%	27.9%	2.3%	29.7%	24%	24.9%
Cerium	0.5%	2.3%	7.2%	3.3%	2.0%	6.1%	50%	43.2%
Praseodymium	0.8%	8.8%	7.4%	5.7%	1.0%	5.8%	6%	4.6%
Neodymium	3.8%	31.0%	30.1%	17.8%	4.0%	20.9%	18%	16.2%
Samarium	2.8%	3.8%	6.3%	4.6%	1.3%	5.5%	1.0%	2.2%
Europium	0.3%	0.5%	0.5%	0.9%	0.0%	0.3%	0.2%	0.3%
Gadolinium	4.7%	2.9%	4.2%	6.0%	5.0%	3.9%	0.7%	1.4%
Terbium	1.1%	0.0%	0.5%	0.7%	1.3%	0.6%	0.1%	0.2 %
Dysprosium	7.1%	0.0%	1.8%	3.8%	8.7%	3.0%	0.1%	0.9 %
Holmium, Lutetium, Thulium, Ytterbium	6.1%	0.4%	1.3%	2.4%	9.0%	2.3%	0.0%	0.8%
Erbium	4.3%	0.0%	0.9%	2.5%	12.7%	7.6%	0.0%	0.5%
Yttrium	66.4%	7.8%	10.1%	24.5%	52.5%	14.3%	0.4%	4.9%
Sum	100%	100%	100%	100%	100%	100%	100%	100%

[34] Some sources are not clear as to whether figures provided refer to t REO/t REO or t REM/ t REM. Most commonly, percentages REO weight percentages are provided. Differences are however small when percentages are provided.

Table 35: REE supply from ion-adsorption clays for low Nd-Fe-B demand scenario (Chapter 4), with secondary supply, assuming demand is met for Dy (Table A1-1) and other REE are produced in a fixed ratio, according to Packey. 2016a) composition

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	22.332	23.467	24.688	25.965	27.306	28.691	30.115	31.582	33.100	34.680	36.338
Cerium	2.501	2.628	2.765	2.908	3.058	3.213	3.372	3.537	3.707	3.884	4.069
Praseodymium	4.587	4.820	5.071	5.333	5.608	5.893	6.185	6.486	6.798	7.123	7.463
Neodymium	14.309	15.037	15.819	16.637	17.496	18.384	19.296	20.236	21.209	22.221	23.284
Samarium	3.723	3.912	4.116	4.329	4.552	4.783	5.020	5.265	5.518	5.781	6.058
Europium	764	803	845	888	934	982	1.030	1.080	1.132	1.186	1.243
Gadolinium	4.918	5.168	5.436	5.718	6.013	6.318	6.631	6.954	7.289	7.637	8.002
Terbium	550	578	608	639	672	707	742	778	815	854	895
Dysprosium	3.075	3.231	3.399	3.575	3.760	3.950	4.147	4.348	4.558	4.775	5.003
Holmium, Thulium, Yt-terbium, Lutetium	1.959	2.059	2.166	2.278	2.395	2.517	2.642	2.771	2.904	3.042	3.188
Erbium	2.063	2.168	2.281	2.399	2.523	2.650	2.782	2.917	3.058	3.204	3.357
Yttrium	18.171	19.095	20.088	21.127	22.219	23.345	24.504	25.697	26.933	28.218	29.568

Table 36: REE supply from ion-adsorption clays, for high Nd-Fe-B demand scenario (Chapter 4), with secondary supply, assuming demand is met for Dy (Table A1-1) and other REE are produced in a fixed ratio, according to Packey. 2016a) composition

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	31.085	34.386	37.599	40.691	43.642	46.439	48.979	51.211	53.065	54.476	55.399
Cerium	3.481	3.481	3.481	3.481	3.481	3.481	3.481	3.481	3.481	3.481	3.481
Praseodymium	6.385	6.385	6.385	6.385	6.385	6.385	6.385	6.385	6.385	6.385	6.385
Neodymium	19.918	22.033	24.091	26.073	27.963	29.756	31.383	32.813	34.002	34.905	35.497
Samarium	5.182	5.182	5.182	5.182	5.182	5.182	5.182	5.182	5.182	5.182	5.182
Europium	1.063	1.063	1.063	1.063	1.063	1.063	1.063	1.063	1.063	1.063	1.063
Gadolinium	6.845	6.845	6.845	6.845	6.845	6.845	6.845	6.845	6.845	6.845	6.845
Terbium	765	765	765	765	765	765	765	765	765	765	765
Dysprosium	4.280	4.735	5.177	5.603	6.009	6.394	6.744	7.051	7.307	7.501	7.628
Holmium. Thulium. Ytterbium Lutetium	2.727	2.727	2.727	2.727	2.727	2.727	2.727	2.727	2.727	2.727	2.727
Erbium	2.872	2.872	2.872	2.872	2.872	2.872	2.872	2.872	2.872	2.872	2.872
Yttrium	25.294	25.294	25.294	25.294	25.294	25.294	25.294	25.294	25.294	25.294	25.294

Table 37: REE supply from LREE-rich mineral deposits (t REM), low Nd-Fe-B demand scenario (Chapter 4) with secondary supply, assuming demand is met for Nd and other REE are produced in a fixed ratio, according to Bayan Obo composition – composition from (Gupta and Krishnamurthy. 2005; Packey. 2016a)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	19.987	22.111	24.501	27.189	30.240	33.684	37.562	41.917	46.794	52.247	58.349
Cerium	42.027	46.494	51.520	57.172	63.587	70.829	78.983	88.140	98.397	109.863	122.694
Praseodymium	4.739	5.242	5.809	6.446	7.170	7.986	8.906	9.938	11.095	12.388	13.834
Neodymium	14.705	16.269	18.027	20.005	22.249	24.783	27.636	30.840	34.429	38.441	42.931
Samarium	843	932	1.033	1.147	1.275	1.420	1.584	1.768	1.973	2.203	2.461
Europium	160	177	197	218	243	270	301	336	376	419	468
Gadolinium	594	657	728	807	898	1.000	1.116	1.245	1.390	1.552	1.733
Terbium	46	51	56	62	69	77	86	96	107	119	133
Dysprosium	47	52	57	64	71	79	88	98	110	122	137
Holmium. Thulium. Ytterbium Lutetium	17	19	21	23	26	29	32	36	40	45	50
Erbium	4	5	5	6	6	7	8	9	10	11	12
Yttrium	358	396	439	487	542	603	673	751	838	936	1.045
Total supply of REE from primary LREE-rich mineral deposits, low Nd-Fe-B demand scenario (in t REM)	83.527	92.405	102.393	113.627	126.376	140.769	156.976	175.174	195.559	218.347	243.848

Table 38: REE supply from LREE-rich mineral deposits (in t REM), high Nd-Fe-B demand scenario with secondary supply, assuming demand is met for Nd, and other REE are produced in a fixed ratio, according to Bayan Obo composition – composition from (Gupta and Krishnamurthy. 2005; Packey. 2016a)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	39.200	47.417	56.877	67.716	80.123	94.325	110.539	129.052	150.208	174.436	202.398
Cerium	82.428	99.707	119.597	142.390	168.479	198.342	232.436	271.365	315.849	366.794	425.592
Praseodymium	9.294	11.242	13.485	16.055	18.997	22.364	26.208	30.598	35.614	41.358	47.988
Neodymium	28.842	34.888	41.847	49.823	58.951	69.400	81.330	94.951	110.516	128.342	148.916
Samarium	1.653	2.000	2.398	2.856	3.379	3.978	4.661	5.442	6.334	7.356	8.535
Europium	315	381	456	543	643	757	887	1.036	1.206	1.400	1.624
Gadolinium	1.164	1.408	1.689	2.011	2.380	2.801	3.283	3.833	4.461	5.180	6.011
Terbium	90	108	130	155	183	216	253	295	343	399	463
Dysprosium	92	111	133	159	188	221	259	302	352	409	474

Holmium. Thulium. Ytterbium Lutetium	34	41	49	58	69	81	95	111	129	150	174
Erbium	8	10	12	14	17	20	24	28	32	37	43
Yttrium	702	849	1.019	1.213	1.435	1.689	1.980	2.311	2.690	3.124	3.625
Sum production from LREE-rich mineral deposits (in t REM) high Nd-Fe-B demand scenario	163.822	198.163	237.693	282.993	334.844	394.195	461.955	539.324	627.735	728.985	845.843

Table 39: Supply/ demand ratio by element (total supply from HREE- and LREE-rich mineral deposits, primary production only), low Nd-Fe-B demand scenario based on Chapter 4. (t REM/t REM)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	129%	131%	135%	138%	142%	146%	151%	156%	161%	166%	172%
Cerium	93%	97%	102%	108%	114%	121%	128%	136%	144%	153%	163%
Praseodymium	129%	130%	130%	130%	130%	130%	130%	130%	130%	130%	130%
Neodymium	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Samarium	561%	539%	512%	481%	455%	432%	411%	390%	370%	351%	334%
Europium	336%	371%	411%	454%	503%	558%	618%	686%	761%	844%	938%
Gadolinium	377%	366%	355%	344%	334%	325%	316%	307%	298%	290%	282%
Terbium	143%	149%	154%	159%	164%	169%	174%	178%	183%	187%	192%
Dysprosium	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Holmium. Thulium. Ytterbium Lutetium	1750%	1705%	1662%	1619%	1577%	1536%	1496%	1457%	1418%	1380%	1342%
Erbium	357%	354%	352%	349%	346%	344%	341%	338%	335%	332%	329%
Yttrium	432%	474%	520%	570%	626%	687%	754%	827%	907%	994%	1090%

Table 40: Supply/ demand ratio by element (total supply from HREE (ion-adsorption clay) - and LREE-rich mineral deposits, primary production only), high Nd-Fe-B demand scenario, based on Chapter 4) (t REM/t REM)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	211%	232%	254%	276%	299%	323%	348%	373%	400%	428%	458%
Cerium	178%	203%	230%	261%	293%	328%	366%	407%	451%	499%	552%
Praseodymium	130%	130%	130%	130%	130%	130%	130%	130%	130%	130%	130%
Neodymium	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Samarium	835%	849%	849%	832%	816%	800%	781%	757%	731%	705%	680%

Europium	498%	583%	677%	781%	897%	1024%	1164%	1319%	1489%	1676%	1883%
Gadolinium	546%	558%	566%	570%	571%	568%	562%	554%	543%	531%	517%
Terbium	164%	172%	179%	186%	192%	199%	205%	211%	217%	223%	231%
Dysprosium	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Holmium. Thulium. Ytterbium Lutetium	2442%	2492%	2519%	2525%	2511%	2479%	2428%	2362%	2280%	2184%	2076%
Erbium	497%	516%	531%	542%	549%	551%	549%	543%	533%	519%	502%
Yttrium	605%	695%	793%	896%	1004%	1119%	1237%	1358%	1480%	1602%	1722%

Table 41: Supply /demand ratio by element (total supply from HREE (ion-adsorption clay) - and LREE-rich mineral deposits and secondary sources), low Nd-Fe-B demand scenario, based on Chapter 4 (t REM/t REM)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	103%	106%	109%	112%	115%	119%	123%	127%	131%	136%	141%
Cerium	77%	81%	86%	91%	96%	102%	108%	115%	123%	130%	139%
Praseodymium	120%	120%	120%	121%	121%	121%	121%	121%	121%	121%	121%
Neodymium	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Samarium	441%	424%	403%	379%	359%	341%	325%	308%	292%	277%	264%
Europium	264%	292%	323%	358%	397%	440%	488%	541%	600%	666%	740%
Gadolinium	295%	286%	278%	270%	262%	255%	247%	240%	233%	226%	220%
Terbium	126%	131%	135%	140%	144%	148%	152%	156%	160%	164%	168%
Dysprosium	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Holmium. Thulium. Ytterbium Lutetium	1359%	1323%	1289%	1256%	1224%	1191%	1158%	1126%	1093%	1062%	1031%
Erbium	277%	275%	273%	271%	268%	266%	264%	261%	258%	255%	252%
Yttrium	335%	368%	404%	443%	486%	533%	584%	640%	700%	766%	839%

Table 42: Supply/ demand ratio by element (total supply from HREE (ion-adsorption clay) - and LREE-rich mineral deposits and secondary sources), high Nd-Fe-B demand scenario, based on Chapter 4 (t REM/t REM)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lanthanum	172%	190%	208%	228%	248%	268%	289%	311%	334%	358%	384%
Cerium	149%	170%	194%	220%	248%	278%	310%	345%	383%	425%	470%
Praseodymium	121%	117%	115%	113%	112%	111%	111%	111%	111%	112%	113%
Neodymium	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Samarium	661%	628%	594%	557%	528%	504%	484%	465%	449%	436%	425%
Europium	394%	430%	472%	520%	575%	640%	715%	801%	903%	1022%	1162%
Gadolinium	429%	405%	384%	366%	350%	335%	323%	313%	304%	296%	291%
Terbium	144%	140%	137%	134%	132%	131%	131%	132%	134%	138%	142%
Dysprosium	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Holmium. Thulium. Ytterbium Lutetium	1898%	1762%	1636%	1520%	1413%	1314%	1222%	1138%	1061%	989%	924%
Erbium	386%	364%	344%	325%	307%	290%	274%	258%	244%	231%	218%
Yttrium	470%	493%	517%	543%	571%	601%	633%	668%	706%	747%	792%

Table 43: Dy and Nd from two primary routes, high Nd-Fe-B demand scenario, based on Chapter 4, primary production only (in t REM)

	2020		2025		2030	
	Dy	Nd	Dy	Nd	Dy	Nd
Ion-adsorption clay deposits	3.964	18.445	5.100	23.733	6.522	30.349
LREE-rich mineral deposits	56	17.579	93	29.298	160	50.271

Table 44: t REM of Dy and Nd from two primary routes, high Nd-Fe-B demand scenario, based on Chapter 4, primary production only

	2020		2025		2030	
	Dy	Nd	Dy	Nd	Dy	Nd
Ion-adsorption clay deposits	5.513	25.653	8.167	38.004	9.918	46.152
LREE-rich mineral deposits	109	34.227	221	81.142	552	173.381

Table 45: Total oversupply for different production mixes, t REM and % reduction in oversupply though recycling (own compilation)

Total REEoversupply from respective production mix (in t REM)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030

Low Nd-Fe-B demand scenario - with recycling	14.243	18.819	24.434	31.110	38.832	47.574	57.369	68.545	81.216	95.506	111.674
High Nd-Fe-B demand scenario - with recycling	99.304	123.493	151.604	184.048	221.174	263.640	311.980	367.264	430.491	502.934	586.685
Low Nd-Fe-B demand scenario - without recycling	43.972	50.654	58.522	67.614	77.967	89.594	102.571	117.269	133.834	152.425	173.334
High Nd-Fe-B demand scenario - without recycling	146.792	182.880	223.494	269.086	319.952	376.787	440.081	510.997	590.600	680.257	782.304
Percentage oversupply reduction through recycling. low demand	68%	63%	58%	54%	50%	47%	44%	42%	39%	37%	36%
Percentage oversupply reduction through recycling. high demand	32%	32%	32%	32%	31%	30%	29%	28%	27%	26%	25%

Table 46: Supply mix from primary sources only, required to meet demand for functional unit, low and high Nd-Fe-B demand scenario, in t REM

	2020_L	2020_H	2025_L	2025_H	2030_L	2030_H
Lanthanum	52.679	86.556	76.859	169.596	115.691	307.679
Cerium	53.464	102.301	87.879	238.540	148.977	503.579
Praseodymium	11.577	19.253	17.049	38.330	25.928	70.666
Neodymium	36.024	59.880	53.031	119.146	80.620	219.533
Samarium	5.807	8.636	7.854	14.538	10.777	21.945
Europium	1.177	1.743	1.587	2.914	2.169	4.355
Gadolinium	7.049	10.198	9.339	16.336	12.459	22.859
Terbium	764	1.092	1.003	1.713	1.323	2.313
Dysprosium	4.020	5.622	5.193	8.425	6.682	10.470
Holmium. Thulium. Ytterbium Lutetium	2.546	3.552	3.283	5.298	4.214	6.521
Erbium	2.664	3.709	3.430	5.503	4.390	6.704
Yttrium	23.851	33.410	30.851	50.236	39.763	62.829
t REM total	201.621	335.952	297.358	670.575	452.992	1.239.453

Table 47: Supply mix from primary and secondary sources, required to meet demand for functional unit, low and high Nd-Fe-B demand scenario, based on Chapter 4 (in t REM)

	2020_L	2020_H	2025_L	2025_H	2030_L	2030_H
Lanthanum	42.319	70.286	62.375	140.764	94.688	257.797
Cerium	44.528	85.909	74.042	201.823	126.763	429.073
Praseodymium	10.756	17.948	15.892	32.828	24.238	61.540
Neodymium	36.024	59.880	53.031	119.146	80.620	219.533
Samarium	4.566	6.835	6.203	9.160	8.518	13.717
Europium	924	1.378	1.252	1.821	1.711	2.688
Gadolinium	5.511	8.009	7.318	9.646	9.735	12.856
Terbium	671	960	881	1.133	1.157	1.427
Dysprosium	4.020	5.622	5.193	8.425	6.682	10.470
Holmium. Thulium. Ytterbium Lutetium	1.976	2.761	2.546	2.808	3.238	2.901
Erbium	2.067	2.880	2.658	2.892	3.369	2.915
Yttrium	18.529	25.996	23.948	26.983	30.613	28.918
t REM total	171.892	288.464	255.339	557.428	391.333	1.043.835

A.3.2 Equations for simple production models, global production of Dy and Nd

1. Primary production only

Dy demand under primary production only scenario (in a specific year, for a specific scenario): $\underline{\mathbf{D_{1,Dy}}}$ [metric tons of Dy metal]

Nd demand under primary production only scenario (in a specific year, for a specific scenario): $\underline{\mathbf{D_{1,Nd}}}$ [metric tons of Nd metal]

The demands for Nd and Dy determine the overall production quantities for REE. i.e. they have to be fulfilled for each year and scenario (100% of demand for each element is met by a combination of supply from ion-adsorption clay deposits (S_{clay}) and mineral deposits (S_{min})). There are two production systems, both of which produce both Nd and Dy (and other REE). Only the relationship for Dy and Nd production from the two production routes needed specifying - The production levels for the joint REE were then derived from the respective ratios in the ore.

$\mathbf{S_{clay}}$: sum of Nd and Dy supply from ion-adsorption clay deposits [metric tons of Dy metal]

$\mathbf{S_{min}}$: sum of Nd and Dy supply from mineral deposits [metric tons of Nd metal]

$$\mathbf{S_{clay} = a_{11} * S_{clay} + a_{12} * S_{clay}} \quad \text{Equ.1}$$

$$\mathbf{S_{min} = a_{21} * S_{min} + a_{22} * S_{min}} \quad \text{Equ.2}$$

$\mathbf{a_{11}}$: wt% of Dy in $\mathbf{S_{clay}}$

$\mathbf{a_{12}}$: wt% of Nd in $\mathbf{S_{clay}}$

$\mathbf{a_{21}}$: wt% of Dy in $\mathbf{S_{min}}$

$\mathbf{a_{22}}$: wt% of Nd in $\mathbf{S_{min}}$

$$\mathbf{D_{Dy} = a_{11} * S_{clay} + a_{21} * S_{min}} \quad \text{Equ.3}$$

Solving Equ. 3 for $\mathbf{S_{clay}}$: $\mathbf{S_{clay} = (D_{Dy} - a_{21} * S_{min}) / a_{11}}$ Equ.4

$$\mathbf{D_{Nd} = a_{12} * S_{clay} + a_{22} * S_{min}} \quad \text{Equ.5}$$

Replacing $\mathbf{S_{clay}}$ in Equ. 5 with Equ. 4, and solving Equ. 5 for for $\mathbf{S_{min}}$ yields:

$$\mathbf{S_{min} = ((a_{12} / a_{11}) * D_{Dy} - D_{Nd}) / (a_{21} * a_{12} / a_{11}) - a_{22}))} \quad \text{Equ.6}$$

The quantities of Nd and Dy produced from each route ($\mathbf{S_{clay}}$ and and $\mathbf{S_{min}}$) can be solved by first calculating the value for $\mathbf{S_{min}}$ (Equ. 6) for each year and scenario. and then inserting the value into Equ. 4.

2. Primary and secondary production

When part of supply of Nd and Dy is met from secondary production ($\underline{\mathbf{S_{Nd.\,rec}}}$; $\underline{\mathbf{S_{Dy.\,rec}}}$), the demand for Dy and Nd from primary sources can be reduced accordingly:

Dy demand from primary sources, under primary & secondary production scenario (in a specific year. for a specific scenario):

$\mathbf{D_{2.Dy}}$ [metric tons of Dy metal]; with $\mathbf{D_{2.Dy} = D_{1.Dy} - S_{Dy.\ rec}}$

Nd demand from primary sources under recycling scenario (in a specific year. for a specific scenario):

$\mathbf{D_{2.Nd}}$ [metric tons of Nd metal]; with $\mathbf{D_{2.Dy} = D_{1.Nd} - S_{Nd.\ rec}}$

The calculation of $\mathbf{S_{clay}}$ and and $\mathbf{S_{min}}$ can then be done as described above in **(1.)**.